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THESIS

EXTREMELY HIGH FREQUENCY (EHF)
LOW PROBABILITY OF INTERCEPT (LPI)
COMMUNICATION APPLICATIONS

by

Robert W. Belcher

March, 1990

Thesis Advisor:

T A Schwendmer

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S)			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Naval Postgraduate School		6b. OFFICE SYMBOL (If applicable) 55		7a. NAME OF MONITORING ORGANIZATION Naval Postgraduate School	
6c. ADDRESS (City, State, and ZIP Code) Monterey, CA 93943-5000			7b. ADDRESS (City, State, and ZIP Code) Monterey, CA 93943-5000		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)		9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code)			10. SOURCE OF FUNDING NUMBERS		
			Program Element No	Project No	Task No
			Work Unit Accession Number		
11. TITLE (Include Security Classification) EXTREMELY HIGH FREQUENCY (EHF) LOW PROBABILITY OF INTERCEPT (LPI) COMMUNICATION APPLICATIONS					
12. PERSONAL AUTHOR(S) BELCHER, ROBERT W.					
13a. TYPE OF REPORT Master's Thesis		13b. TIME COVERED From To		14. DATE OF REPORT (year, month, day) 1990, MARCH, 29	
				15. PAGE COUNT 82	
16. SUPPLEMENTARY NOTATION The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.					
17. COSATI CODES			18. SUBJECT TERMS (continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUBGROUP	Millimeter Wave, EHF, Extremely High Frequency, LPI, Low Probability of Intercept		
19. ABSTRACT (continue on reverse if necessary and identify by block number) A Commander-in-Chief U.S. Pacific Fleet letter to the Chief of Naval Operations, dated September 1989, contains a Command and Control Studies and Analysis Program (C2STAP) proposal for EHF line-of-sight communications. The purpose of this thesis is to address several of the issues raised by the C2STAP proposal by providing: (1) an analysis of the inherent advantages and disadvantages of communications in the EHF spectrum, (2) an analysis of the current and projected future state of EHF technology with respect to potential military applications, (3) a link analysis of an EHF LPI communications link in a specific tactical scenario, and (4) a recommendation to upgrade the Integrated Refractive Effects Prediction System (IREPS) in order to provide an EHF LPI link assessment capability. Although many other applications are referred to, the primary purpose of this thesis is to assess the feasibility, practicality, and tactical benefit of EHF communication systems					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS REPORT <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a. NAME OF RESPONSIBLE INDIVIDUAL Schwendtner, T. A.			22b. TELEPHONE (Include Area code) (408) 646-2056		22c. OFFICE SYMBOL 32

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted
All other editions are obsoleteSECURITY CLASSIFICATION OF THIS PAGE
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Extremely High Frequency (EHF)
Low Probability of Intercept (LPI)
Communication Applications

by

Robert W. Belcher
Captain, United States Marine Corps
B.S., North Carolina State University, 1977

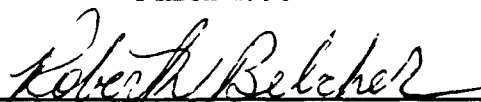
Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN TELECOMMUNICATIONS SYSTEMS MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
March 1990

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ABSTRACT

A Commander-in-Chief U.S. Pacific Fleet letter to the Chief of Naval Operations, dated September 12, 1989, contains a Command and Control Studies and Analysis Program (C2STAP) proposal for EHF line-of-sight communications. The purpose of this thesis is to address several of the issues raised by the C2STAP proposal by providing:

- an analysis of the inherent advantages and disadvantages of communications in the EHF spectrum,
- an analysis of the current and projected future state of EHF technology with respect to potential military applications,
- a link analysis of an EHF LPI communications link in a specific tactical scenario, and
- a recommendation to upgrade the Integrated Refractive Effects Prediction System (IREPS) in order to provide an EHF LPI link assessment capability.

Although many other applications are referred to, the primary purpose of this thesis is to assess the feasibility, practicality, and tactical benefit of EHF communication systems.

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I. INTRODUCTION

A. PURPOSE

A Commander in Chief U.S. Pacific Fleet (CINCPACFLT) letter to Chief of Naval Operations, dated 12 September 1989, contains a Command and Control Studies and Analysis Program (C2STAP) Proposal for Extremely High Frequency (EHF) Line-of-Sight Communications [Ref. 1]. The letter proposes that a study be initiated in order to assess the technical and tactical feasibility of low probability intercept (LPI) communication systems operating in the EHF spectrum.

This thesis addresses the issue raised in the C2STAP by providing:

- an analysis of the inherent advantages and disadvantages of communications in the EHF spectrum,
- an analysis of current and projected future EHF technologies with respect to potential military applications, and
- a link analysis of an EHF LPI communication system in a specific tactical scenario.

The feasibility, practicality, and benefit of EHF LPI communication systems are areas of consideration for this thesis.

B. THESIS SCOPE

Chapter I provides background information on the EHF spectrum and a brief history of millimeter wave applications.

Chapter II describes the propagation characteristics of millimeter waves and defines the parameters which have the most impact on EHF LPI communications.

Chapter III gives an overview of the current state of millimeter wave technologies: power sources, circulators, mixers, and antennas. Because of its importance for future system applications, EHF solid-state technology is also addressed.

Chapter IV provides information on several currently deployed EHF LPI system applications and programs under development.

Chapter V discusses EHF link assessment in general then evaluates the LPI performance of a hypothetical satellite communication system to illustrate the performance advantage of EHF LPI communications. The chapter concludes with a proposal and an endorsement for an enhanced version of the U.S. Navy's Integrated Refractive Effects Prediction System (IREPS). An enhanced IREPS has the potential to provide a rapid-response, on-scene, EHF LPI assessment capability.

Chapter VI summarizes EHF LPI communication system advantages and disadvantages, as well as a the most significant EHF technological trends.

C. BACKGROUND

1. EHF Spectrum

The EHF portion of the electromagnetic spectrum lies between 30 and 300 GHz, corresponding to wavelengths of 10 to 1 mm, hence the term millimeter wave. As shown in Figure 1., the millimeter wave spectrum lies between the microwave and infrared segments of the electromagnetic spectrum. Table 1. shows the various letter-band designations used in this segment of the spectrum [Ref. 2]. Henceforth, a looser definition of EHF will be adopted (based on the characteristics of the waves) so that 20 GHz is also included for purposes of analysis.

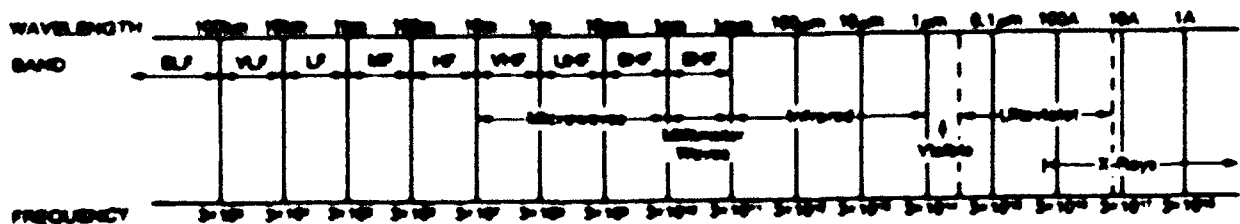


Figure 1. The Electromagnetic Spectrum

TABLE 1. FREQUENCY-BAND DESIGNATIONS [Ref. 2]

Microwave and radar usage		Official joint chiefs of staff band designation	International telecommunications union, Geneva		EIA JAN standard waveguide	
United Kingdom usage	United States usage		Band designation	Metric designation	Staggered series of rectangular guide sizes (no ridges)	
100					90-140 GHz	100
		M 60-100 GHz			WR 10 75-110 GHz	
70	V-BAND 50-75 GHz		BAND NO. 11 EHF 30-300 GHz	MILLIMETRIC	WR 12 RG 99 60-90	70
					WR 13 RG 98 50-75	
50		L 40-60			WR 19 40-60	50
	V-BAND 46-56				WR 22 RG 97 33-50	
40	Q-BAND 40-70					40
	Q-BAND 36-46				WR 28 RG 96 26.5-40	
30	Q-BAND 27-40	K 20-40				30
			BAND NO. 10 SHF 1-30	CENTIMETER	WR 42 RG 53 18-26.5	
20	K-BAND 18-27				WR 51 15-22	20
	K-BAND					

2. Millimeter Wave History

The exploitation of new frequency regions has always led to technological advances in the history of radio communication. The EHF region is a new frontier. This region has seen significant advances in recent years in the development of transmitters, receivers, devices, and components. Progress is now occurring in the evolution of systems applications in such fields as communications,

radar, radiometry, remote sensing, missile guidance, radio astronomy, and spectroscopy.

Millimeter wave systems are only now starting to be widely used, but they have a history which is nearly as long as that of radio waves. Interest in the development of millimeter wave components and systems dates back to the early 1940's, but the first commercially useful components for the 20 to 300 GHz region did not appear until almost 30 years later. The reasons for this gap can be generally related to a lack of understanding of atmospheric propagation characteristics and the absence of efficient millimeter wave components.¹ It was not until many years later that the atmospheric transmission characteristics at millimeter wavelengths were adequately understood. [Ref. 3]

After the introduction of low-loss circular waveguides in the early 1950's, Bell Laboratories became very active in the investigation of wideband millimeter wave communication systems. The late 1960's saw the introduction the solid state IMPATT (Impact Avalanche and Transit Time) oscillator which finally made it possible to construct

¹ As an example, the first K band radar, which was developed by MIT in 1942, performed poorly because it operated near the water vapor absorption line at 20 GHz.

compact and potentially low cost radar and communication systems.

The current resurgence of interest in millimeter waves is due, at least in part, to the following important considerations:

- there are limitations to what can be accomplished with infrared and optical systems because of the effects of fog, dust and other environmental phenomena, the microwave spectrum is becoming crowded, and
- millimeter wave communication systems have an inherent low probability of intercept (LPI) capability which can be exploited.

Currently, the 30 to 100 GHz segment of the EHF spectrum has seen the heaviest system development, while the range above 100 GHz has seen a concentration of research on components, devices and techniques. Numerous proposed EHF systems are technologically feasible and may fill a need, but they are not yet economically feasible. Recent technological advances in mm-wave communications have been significant however, and indicate a trend toward increased system development. [Ref. 4]

D. EHF CHARACTERISTICS

1. Wave Propagation

In general, the atmospheric propagation effects of the EHF spectrum dominate considerations relating system applications. This is true even for satellite-to-satellite communications outside the atmosphere, since frequencies may be chosen for which the atmosphere is opaque, thus preventing detection by ground based interceptors. Terrestrial systems may avoid signal intercept by operating at frequencies of high atmospheric absorption thus limiting the range of the transmission. Since this aspect is, in many cases, the primary consideration for the successful employment of EHF systems, it is covered in more detail in Chapter 2.

2. Beamwidth

A second important characteristic of the EHF segment of the spectrum is that for a given antenna size, beamwidths are smaller and gains are higher for millimeter wave frequencies than for microwave frequencies. Figure 2 illustrates this point. At 94 GHz, beamwidth is two degrees or less, which makes it highly jam resistant.

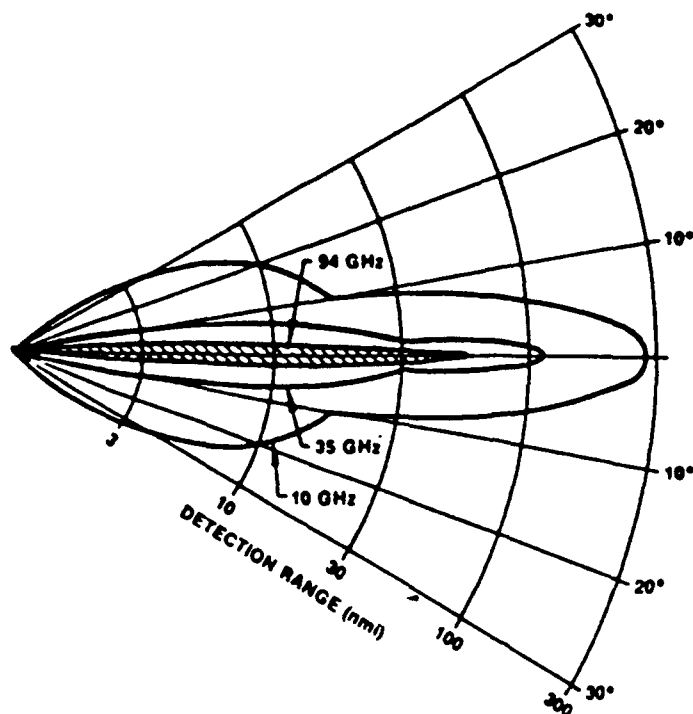


Figure 2. EHF Antenna Patterns [Ref. 5]

3. Bandwidth

The third characteristic is relative spectral "size" or bandwidth. The entire frequency space below 1 GHz, which is so carefully regulated and allocated, occupies just 1% of the bandwidth at 100 GHz [Ref. 6]. The potential in this large bandwidth is not in replacing services which exist at lower frequencies, but in providing new capabilities such as:

- high data rate systems
- wide-band spread-spectrum systems for reduced multipath and clutter, and
- systems with high immunity to jamming and interference because of the large number of frequencies that are available for use.

E. EHF APPLICATIONS

Table 2 lists over 60 EHF applications grouped under the headings of radar, communications, radiometry, and instrumentation. The list is included here to show the broad range of current and proposed EHF applications. EHF LPI communication applications are addressed in detail in Chapter IV.

TABLE 2. EHF APPLICATIONS [Ref. 7]

<i>Radar</i>	
Low angle tracking	Remote sensing of the environment
Secure military radar	Surveillance
Interference free radar	Target acquisition
Cloud sensing radar	Missile guidance
High resolution radar	Navigation
Imaging radar	Obstacle detection
Ground mapping	Clutter suppression
Map matching	Fuses
Space object identification	Harbor surveillance radar
Lunar radar astronomy	Airport surface detection radar
Target characteristics	Landing aids
Weather radar	Air traffic control beacons
Clear air turbulence sensor	Jet engine exhaust and cannon blast
Target designators	Beam riders
Range finders	Passive seekers
Detection/classification of ground vehicles	Imaging
LPI radar	Hand-held radar
Radar cross-section measurements	Active missile seekers (terminal guidance)
<i>Communications</i>	
Secure military communications	Satellite to satellite communications
Point to point extremely wideband communications	Inter satellite relays
Spacecraft communications during blackout	Earth to space communications
Interference free communications	Retroreflector communications
	LPJ communications
	Railroad communications
<i>Radiometry</i>	
Remote sensing of the environment	Ground target detection
Radio astronomy	Missile detection
Radio sextant	Missile guidance
Ship detection	Clear air turbulence sensor
Space-based radiometers	
<i>Instrumentation</i>	
Plasma diagnostics	Automatic braking
Rocket exhaust plume measurements	Spectroscopy
Remote vibration sensor	Prediction of blast focusing
Model radar cross-section measurements	Classroom demonstration of optics

II. PROPAGATION CHARACTERISTICS

A. ATMOSPHERIC PROPAGATION

1. Absorption by Gases

Absorption due to water vapor and oxygen is the principal cause of millimeter wave attenuation in atmospheric propagation. The effect in a clear atmosphere at sea level is almost negligible except at frequencies where the absorption line of water vapor or oxygen are located. As shown in Figure 3, the attenuation due to oxygen molecule and water vapor absorption is highest around 60, 119, and 183 GHz. [Ref. 5] Because atmospheric pressure and water vapor density generally decrease with height, these absorption coefficients are altitude dependent and decrease rapidly with altitude.

2. Precipitation Effects

The attenuation of millimeter wave transmissions due to precipitation is even more severe than that due to absorption by gases in the atmosphere. Rain drops, snow flakes, ice crystals, hail stones, cloud and fog droplets are all small dielectric scatters.

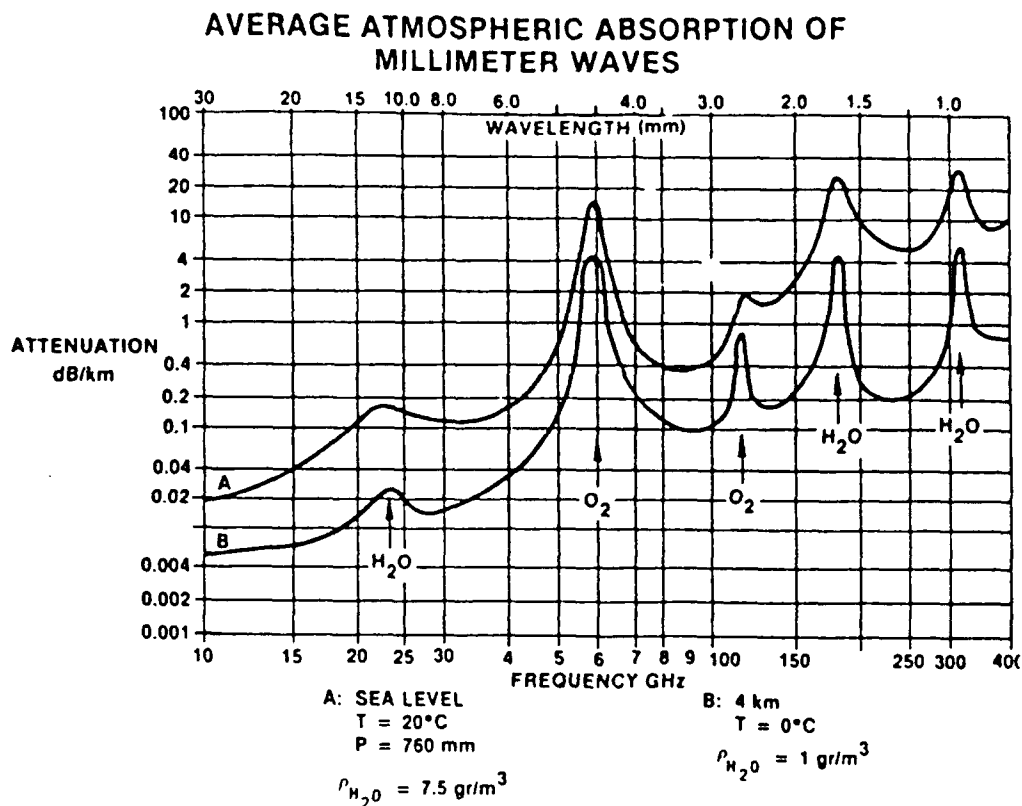


Figure 3. Atmospheric Absorption of MM-Waves [Ref. 5]

For simple, spherical, particle shapes, scattering properties can be readily calculated, but for the more complex shapes and sizes actually assumed by precipitation, scattering properties can only be approximated after a long and tedious numerical analysis. For the estimation of attenuation however, simple model calculations are adequate.

The depolarization of millimeter waves by precipitation is dependent on the type of incident

polarization as well as the size, shape, and orientation of the precipitation. Actual depolarization effects from precipitation can be computed from experimental data taken on a dual polarized propagation link. [Ref. 8]

a. Rain

Figure 4 depicts worldwide rain regions along with percent of occurrence for rainfall in excess of the given rate. Figure 5 shows that specific attenuation increases with increasing frequency and rain rates. These two Figures can be used to approximate the attenuation due to rain for a specific application. Although these figures are based on experimental data, there is good correlation between measurements in natural or emulated rain and theoretical calculations. [Ref. 8]

b. Snow, Ice and Hail

Attenuation due to frozen particles is of little importance at frequencies less than 60 GHz. At higher frequencies, the attenuation becomes more important but there has been little research done to model or measure the effects. Hail is of importance less than .001% of the time in most climate regions and is usually ignored in the design of communications systems. [Ref. 9]

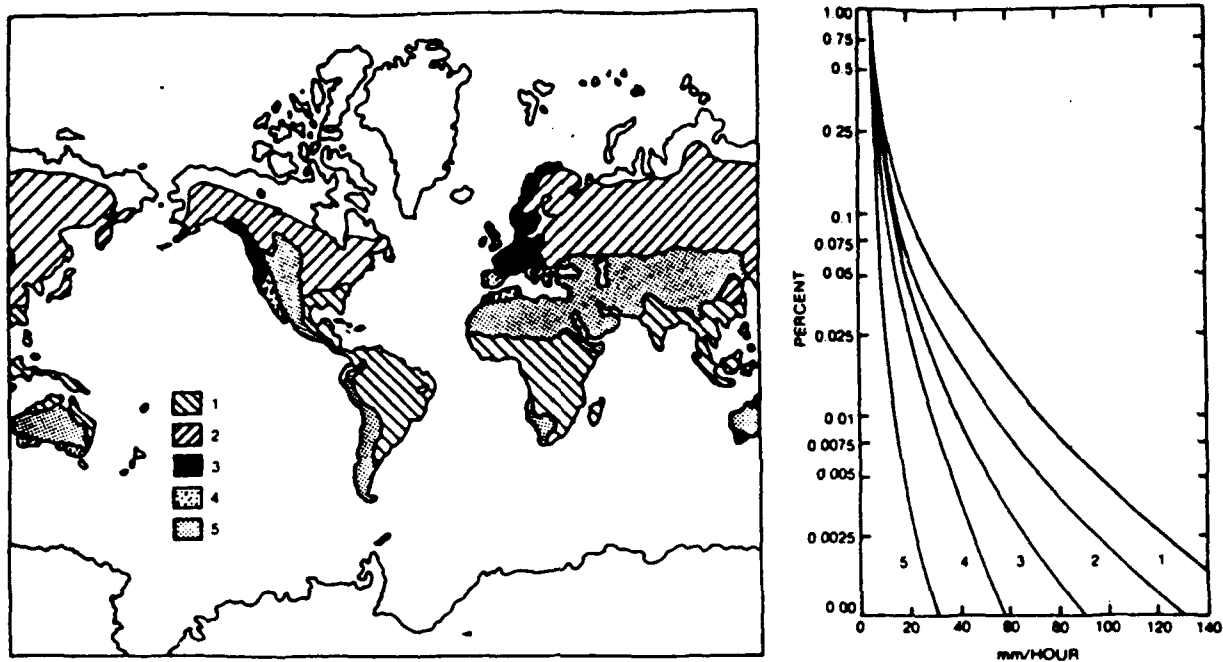


Figure 4. World Rainfall Distribution [Ref. 7]

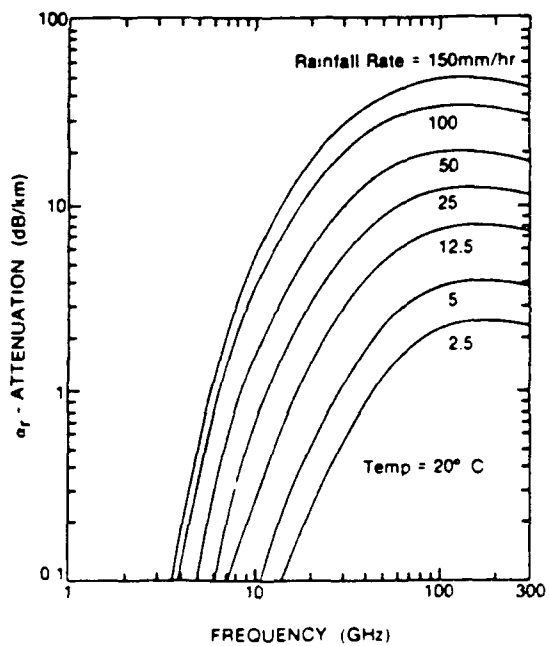


Figure 5. Rain Attenuation Coefficients [Ref. 7]

c. Fog and Clouds

Attenuation due to fog is less serious than that due to rain since the water content is low, varying from 1 g/m³, for thick fog, to about .04 g/m³ for moderate fog. For clouds, water content depends on cloud type, ranging from about 0.1 g/m³ to 2-3 g/m³. Figure 6 shows that attenuations in fog or clouds increases with frequency but decreases with ambient temperature in the EHF region. [Ref. 8]

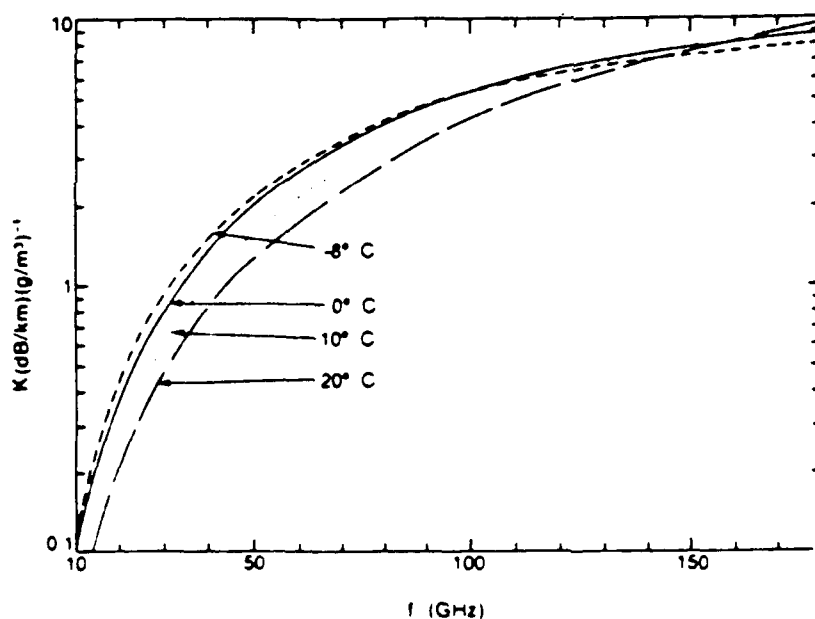


Figure 6. Cloud and Fog Attenuation [Ref. 7]

3. Ducting

Other phenomena, not normally as significant as gaseous and precipitation attenuation, may also effect the performance of a millimeter wave system. These include:

- evaporative ducting,
- reflectivity of clouds and rain,
- thermal noise in the atmosphere,
- atmospheric turbulence, and
- multipath fading.

Because of its significant effect on LPI communications, evaporative ducting must be given special consideration.

[Ref. 10]

1. Mechanism

Atmospheric layers, created by a rapid decrease of moisture above the surface of the earth, are called ducting layers if their refractivity gradients differ enough to refract electromagnetic energy back toward the surface of the earth. Energy refracted back toward the surface of the earth can be redirected upwards again, keeping the wave confined between two horizontal surfaces. This results in a field whose power flux density decreases inversely with distance, rather than inversely with the square of the

distance, as is expected in free space. This decrease in the normal attenuation caused by free space loss can dramatically increase the range of radio frequency transmissions. [Ref. 11]

b. Scope

Conditions are best for long range duct propagation over the ocean where ducts can span distances of more than a 1000 km. Evidence of how strongly the evaporation duct influences propagation at millimeter wavelengths was documented by a year long experiment conducted by the Naval Ocean Systems Center. Results from more than 2000 hours of measurements, at 94 GHz, on a 40.6 km, over-water path, consistently showed that there was in excess of 60 dB more power available at the receiver than would be expected using the standard (4/3 earth) propagation model. [Ref. 12]

B. PROPAGATION IN DUST AND SMOKE

The ability of millimeter waves to propagate almost unattenuated through smoke, dust, and debris is one of the biggest advantages afforded by EHF system applications. Tests have indicated negligible attenuation for millimeter waves propagation through vehicle-generated dust. Tests of atmospheric nuclear effects, evaluated for near surface

detonation in terms of atmospheric ionization and refractive index fluctuations, indicate that under the most intense battlefield conditions, only momentary loss of signal may occur when millimeter wave systems are employed. [Ref. 13]

III. MILLIMETER WAVE COMPONENT TECHNOLOGY

A. DEVICES AND COMPONENTS

1. Sources

The successful use and application of millimeter waves depends to a large degree on the availability of appropriate power sources. Technology exists for both vacuum tube and solid-state power sources to cover energy generation over the complete millimeter wave spectrum. The power level obtainable from the solid state sources is low in comparison to the tube sources, but the technology in solid state sources is advancing rapidly. Tube sources have a more narrowly defined area of application however, because of their size and the high voltage requirement of their power supply.

a. Tubes

Millimeter wave tubes may be classified as either slow-wave or fast-wave devices. The slow-wave devices such as cross-field amplifiers (CFAs), magnetrons, traveling-wave tubes (TWTs), and backward-wave oscillators (BWOs) are primarily scaled down versions of their microwave region source counterparts. Fast-wave devices such as gyrotrons,

ledatrons, and peniotrons, reflect new, still evolving technologies which allow these devices to produce much higher power levels. As shown in Figure 7, for most mm-wave transmitter applications, TWTs are the optimum choice. The typical system requirements that are met by TWTs are shown in Table 3. [Ref. 14] [Ref. 15]

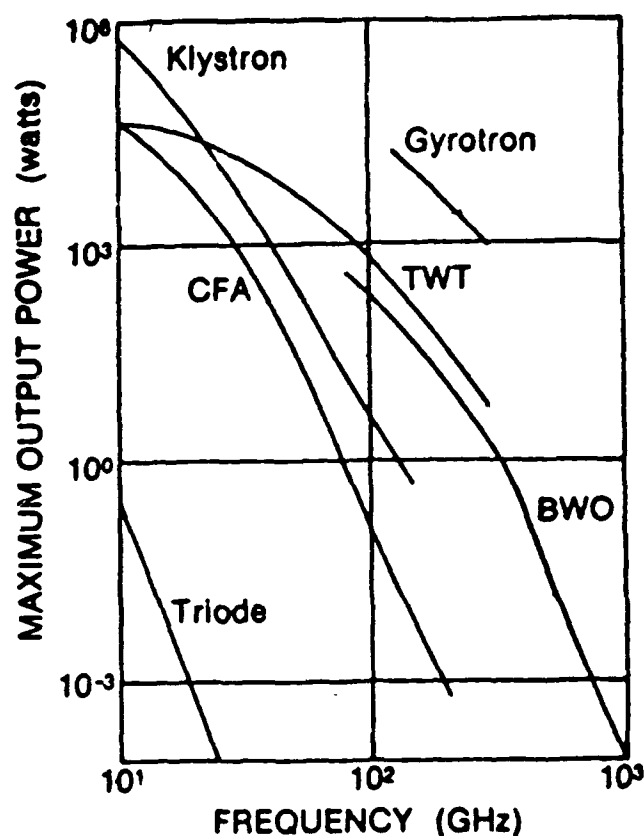


Figure 7. Power Output of Tube Sources [Ref. 16]

TABLE 3. SYSTEM REQUIREMENTS MET BY TWTs [Ref. 15]

Frequency: 1 to 100 GHz

Bandwidth: can be over two octaves

Gain: 10 dB to over 60 dB

Output power: 1 W to over 100 kW

Operating environment: ground, sea-level, airborne
outer space, or any combination.

TWTs may be classified by application, output power level, frequency range, or any other attribute that is relevant to the system application. The features that influence the design of TWTs for space communications applications include:

- long life and high reliability,
- high efficiency,
- moderate Bandwidth,
- moderate power output, and
- low phase and gain distortion.

The features that influence the design of TWTs for terrestrial communication applications include:

- moderate bandwidth,
- moderate to high power, and
- low distortion.

The present state of the art for space and terrestrial communication applications of TWTs is shown in Figures 8 and 9 respectively. [Ref. 15]

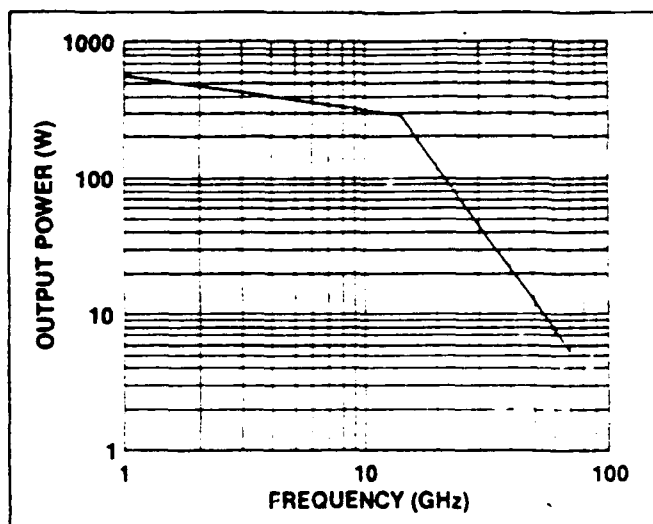


Figure 8. Space Communication TWTs [Ref. 15]

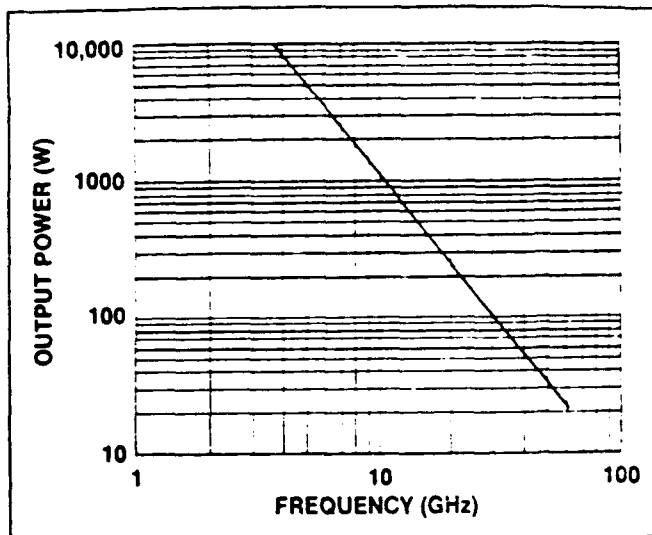


Figure 9. Terrestrial Communication TWTS [Ref. 15]

b. Solid-State Sources

The availability of improved solid-state sources has contributed to the growth in millimeter wave applications. While these sources provide less output power, they are smaller and require much lower voltages than vacuum-tubes. The most obvious improvements in solid-state sources in the past few years have been the increased power output and the higher operating frequencies.

In the 20-30 GHz range, the gallium arsenide (GaAs) metal semiconductor field-effect transistor (MESFET) has become the dominate choice because of its power, efficiency and reliability. MESFET-based monolithic

microwave/mm-wave integrated circuits (MMICs) have also made significant progress in this frequency range.

At frequencies above 30 GHz, IMPATT (Impact Avalanche and Transit Time) and transferred electron oscillators or Gunn devices dominate most system applications. Figure 10 summarizes the current performance characteristics of the most commonly used solid-state power sources. [Ref. 17]

2. Mixers

In mixer design, the performance parameters of primary concern are the operation bandwidth and the conversion loss. The latter consists of the intrinsic junction loss of the ideal diode, and mismatch losses at the RF and IF ports. In the past decade, mixer noise temperatures have been lowered by an order of magnitude. Extensive research has been done on both the mixer structure and the diode materials. Figure 11 shows typical mixer noise figure performance for EHF frequencies from 30 to 140 GHz. [Ref: 2]

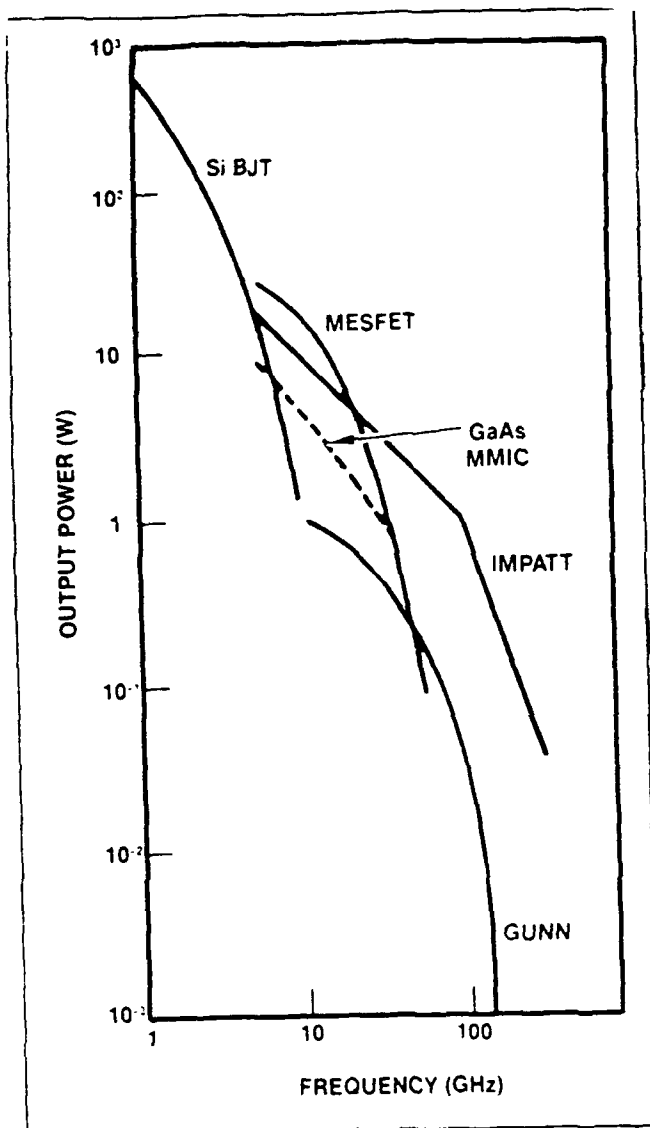


Figure 10. Output of Solid-State Devices [Ref. 17]

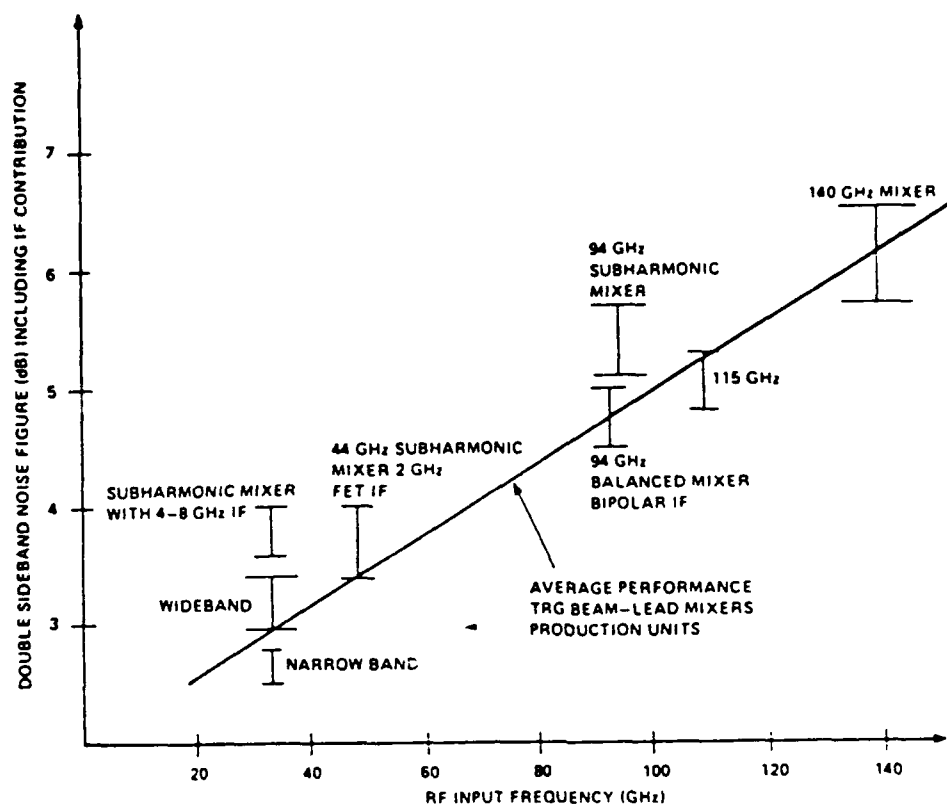


Figure 11. Performance of MM-Wave Mixers [Ref. 2]

3. Circulators

Circulators are the most widely used ferrite device in mm-wave system applications. The most prevalent use of circulators is for signal separation, as in the separation of transmitted and received signals at the base of an antenna. Circulators are made in switched as well as fixed versions, but the two principle classifications are differential phase-shift circulators and Y-junction circulators.

Differential phase-shift circulators are generally used in applications where extremely high peak or average power must be handled. Switching versions of differential phase-shift circulators allow control of signal path and variable power division between paths.

Y-junction circulators are the most commonly used, and are further subdivided into three categories: waveguide, coaxial, or microstrip (drop-in), according to the purpose of their terminal connector.

The most important characteristics of circulators are insertion loss, isolation, input SWR, frequency band of operation, power handling capability, and size and weight. In communications systems, the design choice between differential phase-shift and Y-junction circulators will be determined by which of these characteristics is most critical to the system application. Tables 4 and 5 show the current characteristics of differential phase shift and Y-junction circulators respectively. [Ref. 18]

TABLE 4. PHASE-SHIFT CIRCULATOR PERFORMANCE [Ref. 18]

Operating Frequency (GHz)	Power Handling Peak (MW)	Avg. (kW)	Maximum Insertion Loss (dB)	Minimum Isolation (dB)	SWR (max.)	Coolant	Weight (lbs.)
1.25 to 1.35	2.5	150	0.5	25	1.2	Liquid	1200
2.7 to 3.15	5	100	0.5	20	1.2	Liquid (pressurized waveguide)	116
3.1 to 3.4	2.5	50	0.5	20	1.15	Liquid	45
5.925 to 6.405	CW	25	0.2	23	1.10	Liquid	35
7.75 to 8.35	0.025	25	0.25	25	1.2	Liquid (pressurized waveguide)	12.5
10.2 to 10.5	CW	10	0.4	20	1.2	Air (pressurized waveguide)	1.5
15 to 17.2	0.005	3	0.4	20	1.15	Air	6
27.5 to 30	CW	0.5	0.5	20	1.2	Air	
94 to 96	0.01	0.030	1.3	18	1.3	Air	0.6

TABLE 5. Y-JUNCTION CIRCULATOR PERFORMANCE [Ref. 18]

Operating Frequency (GHz)	Power Handling Peak (MW)	Avg. (kW)	Maximum Insertion Loss (dB)	Minimum Isolation (dB)	SWR (max.)	Coolant	Weight (lbs.)
1.25 to 1.35	1	10	0.3	20	1.15	Liquid	60
2.998	3.5	3.5	0.25	20	1.2	Air	8.8
2.9 to 3.1	2	5	0.25	20	1.2	Liquid	7.5
5.4 to 5.9	0.3	3	0.3	20	1.2	Liquid	12
5.4 to 5.9	0.5	1	0.25	20	1.2	Air	2.5
5.4 to 5.9	0.3	3	0.3	20	1.2	Forced air	7
8.5 to 9.6	0.25	0.25	0.3	23	1.2	Air	10
11.7 to 12.1	CW	1	0.1	24	1.1	Air	0.45
15.9 to 16.5	0.10	0.10	0.5	18	1.3	Air	0.5
16.5 to 17	0.015	0.5	0.2	20	1.2	Air	0.5
43.5 to 45.5	0.002	0.050	0.2	21	1.25	Air	0.3
91 to 97	0.001	0.030	0.3	20	1.2	Air	0.2

4. Antennas

Antenna research and development at EHF frequencies has not received as much attention as has sources, circuits and other communication components. This is probably because the technology has simply been extended upward from the microwave region and downward from the optical region.² This situation is changing however, because as new mm-wave system applications are identified, antennas, like other component parts, are continually being reexamined in light of the new requirements. [Ref. 19]

In some applications however, in order to reduce cost, size, and weight, the design of a flat, low profile antenna which can be fabricated as an integral part of the system is desired. Microstrip, dielectric rod, and leaky wave antennas are being developed to meet these requirements.

Antennas for future EHF systems will be designed through the aid of computers. Computer programs for the design and analysis of shaped reflector systems, beam-waveguide transmission lines, frequency selective

² The performance characteristics and design principles of conventional antennas such as the reflector, lens, and horn have been well established at microwave frequencies; thus, upward conversion to the millimeter wave region for these antennas is fairly straightforward.

surfaces, and corrugated feed horns are being developed and will be used extensively in the future as performance requirements become increasingly stringent. [Ref. 19]

The importance of antenna size and shape with respect to system application can be seen by the range of antenna requirements contained in Table 6.

B. INTEGRATED CIRCUIT TECHNOLOGY

1. Introduction

In 1987, the Department of Defense started a Microwave/Millimeter-wave Integrated Circuits (MMIC) program by awarding 16 phase-0 contracts worth a total of \$12.5 million. These 16 industry teams are competing for a share of what is a \$536 million, seven-year effort. Three finalists will be selected in April 1991 to begin demonstrating MMIC technology in new weapon systems.

The two criteria for the successful implementation of MMIC device technology into future military systems are affordability and producibility. Just as silicon transistors replaced vacuum tubes at UHF and lower frequencies decades ago, MMIC devices are expected to replace TWTs at the L, S, C, X, Ku, and Ka bands. [Ref. 20]

TABLE 6. MM-WAVE ANTENNA APPLICATIONS [Ref. 19]

System type	Applications	Typical antenna requirement
Radar (35, 94, 140, 220 GHz)	Active fuses, LPI radar, target designators, high-resolution radar, search and track radar, range finders, anticollision devices, velocity indicators for railways and traffic, active missile seekers	<ol style="list-style-type: none"> 1. Resolution determines gain > 30 dB 2. Sidelobes < -25 dB 3. Antenna efficiency $> 80\%$ 4. Frequency or phase-shift scanning (possibly)
Radiometry (35, 94, 140, 220 GHz)	Terrain imaging, astronomy, metrology, plasma diagnostics, visual aids for the blind, classifiers, target seekers	<ol style="list-style-type: none"> 1. Gain ≥ 30 dB 2. Sidelobes ≤ -30 dB 3. Beam scanning 4. Wideband operation for good image resolution 5. Low-loss antenna to reduce noise temperature
Electronic countermeasures (35, 94, 140, 220 GHz)	Electronic warfare, speed-radar detectors	<ol style="list-style-type: none"> 1. Hemispherical coverage 2. Wider bandwidth $\sim 5\%$
Submunitions (35, 94, 140, 220 GHz)	Terminal guidance of shells, smart weaponry	The electrical requirements are those for radar and radiometry, but the size, weight, and cost factors are more severe.
Communications [60 GHz for low probability of intercept (LPI)]	High-capacity trunk lines, short distance links, satellite communications, secure LPI links, ship-to-ship	<ol style="list-style-type: none"> 1. Beamwidth and system power budget set gain required 2. Low sidelobes < 25 dB for security and jamming protection 3. Large bandwidth for frequency hopping techniques ($\sim 5\%$) 4. Lightweight, compact for hand-held or portable systems

2. MMIC Applications

MMIC device technology is providing the capability for complex signal processing in mm-wave system applications. Signal processing applications are progressing as fast as the advancements in analog and digital component technologies will permit. Generally, three basic requirements exist:

- greater information rate (bandwidth)
- greater pulse information structure, and
- greater sensitivity and dynamic range.

To meet these requirements, metal semiconductor field effect transistor (MESFET), heterojunction bipolar transistor (HBT), and high electron mobility transistor (HEMT) MMIC chips are emerging to provide signal architecture structures previously considered unattainable.
[Ref. 21]

The tradeoff of analog versus digital signal processing is a hardware consideration that depends on the available component technologies. In future applications, the analog portion of mm-wave systems may be implemented on a few MMIC chips.

3. Future Trends

The current capabilities and projected future trends of MMIC signal processing are shown in Table 7. [Ref. 21] Rapid advances in MMIC technology are predicted to push mm-wave signal processing techniques to higher performance and integration levels. This will help make the production of complex systems, like multibeam mm-wave communications, practical and affordable. [Ref. 14]

TABLE 7. MMIC PROCESSING THROUGHPUT PREDICTIONS [Ref. 20]

MMIC Chip Parameter	MMIC Technology Evolution				
	1975	1980	1985	1990	1995
Complexity level	discrete	single-stage	microcell	macrocell	subsystem
Devices	1	3 to 6	5 to 15	15 to 50	50 to 500
Maximum frequency (GHz)	—	10	30	60	100
Minimum gate size (μm)	1	1	0.5	0.25	0.10
Throughput (devices GHz)	—	—	20	200	2000

IV. EHF LPI COMMUNICATION APPLICATIONS

A. TERRESTRIAL SYSTEMS

VHF and UHF radios have traditionally been the primary means of communications within forward area combat units. It is with these radios that commanders direct and control their combat and combat support forces during all phases of an operation. In many cases however, the success of an operation depends on massing and coordinating forces in a covert manner. Because of this requirement, the radios that normally support the commander must remain silent.

EHF terrestrial communication systems can generally be grouped into one of two categories:

- those where the carrier frequency is chosen to be in a range of low atmospheric attenuation (e.g., the 30-40 GHz window) in order to maximize the range of transmission, or
- those where the carrier frequency is chosen to be in a range of high atmospheric attenuation (e.g., near 60 GHz) in order to limit the transmission range.

EHF LPI communications (the latter category) provide a capability which can not be degraded by battlefield conditions or exploited by enemy intelligence functions, jamming, or antiradiation missiles. Figure 12 shows the LPI

advantage of EHF transmissions over low power VHF transmissions [Ref. 22].

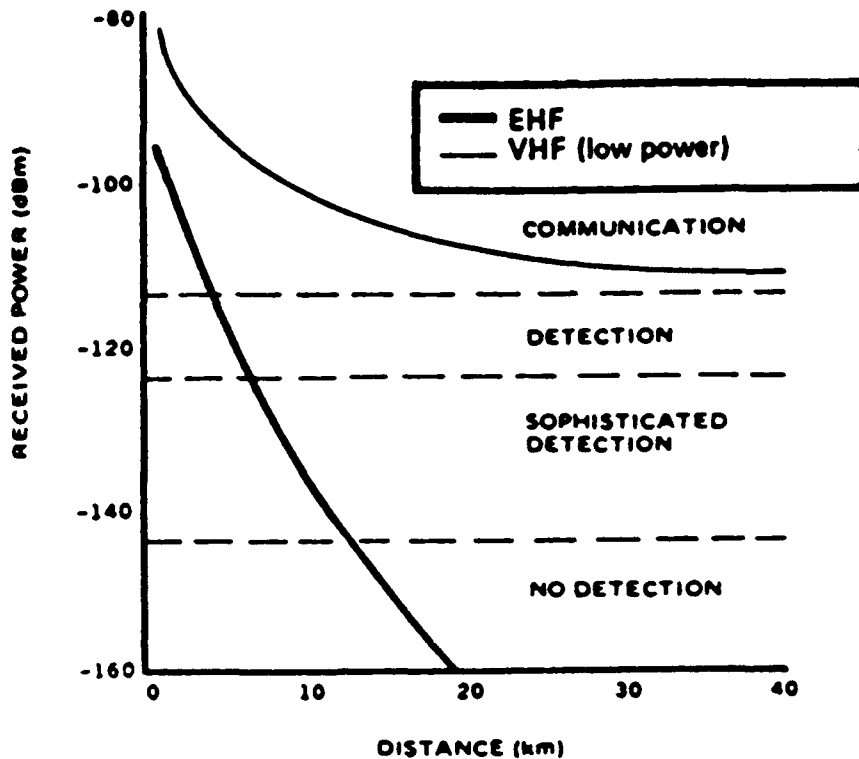


Figure 12. EHF LPI Characteristics [Ref. 22]

1. Mobile Intercept-Resistant Radio (MISR)

The MISR was developed as a result of an extensive effort by the U.S. Army Communications-Electronics Command (CECOM). One of a family of mm-wave radios developed by CECOM, the MISR operates in the 54-58 GHz region. Atmospheric clear air oxygen absorption in this region varies from about 2 dB/km to about 12 dB/km (see Figure 3).

MISR operating procedures call for a communications link to be initially established at 54 GHz, and then tuned to a higher frequency in order to minimize the intercept range of the link. If it rains, the radio is then tuned back toward 54 GHz in order to decrease the signal attenuation.

Communication links of up to 5 km have been established at 54 GHz and up to 2.5 km at 58 GHz, with a significant reduction in the intercept range. Two types of antennas can be used with the radio. A directional horn is used to provide covertness and high gain, and a biconical horn is use to provide omnidirectional coverage in azimuth. Narrow-band omnidirectional links have been established at ranges exceeding 1 km at 54.5 GHz. Table 8 lists the MISR system parameters. [Ref. 23] Appendix A contains additional information on the CECOM EHF radio developmental program.

TABLE 8. MISR PARAMETERS [Ref. 23]

Frequency band	54-58 GHz
Transmit power	100 mW
Data rate	4.9 Mb/s digital data or analog television channel
Receiver noise figure	11 dB
Antenna gain	
Directional	25 dB (BW 2.8°, worst sidelobe -25 dB)
Omni	3 dB (BW 42° elevation)
Antenna size	(directional) horn/lens, 6 inch diameter
Range	1 to 5 km

2. EHF Applique

The EHF applique provides the operator with a system which can quickly transition from LPI to normal range communications in response to rapid changes in the tactical situation. The EHF applique was designed to supplement VHF or UHF radios (see Figure 13) by providing a short-range LPI capability in a strap-on application. In this system, a VHF or UHF signal normally transmitted by a host radio is heterodyned up into the region of the spectrum near 60 GHz

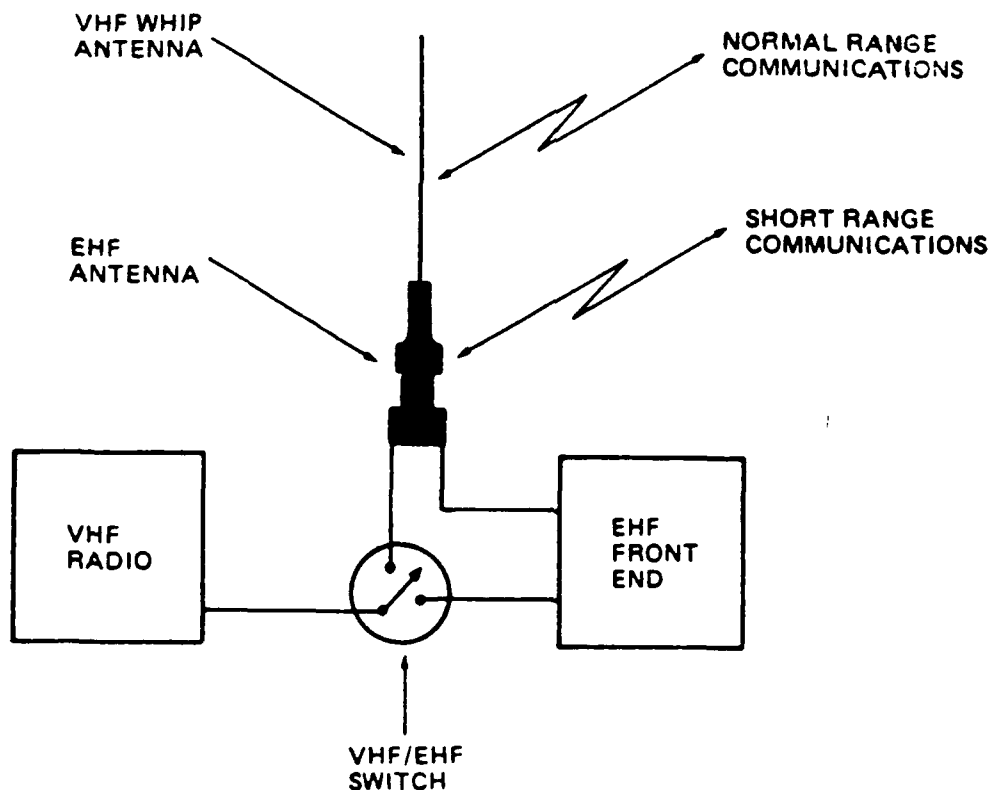


Figure 13. EHF Applique Concept [Ref. 24]

and transmitted by an appropriate antenna. Signals received by the antenna are down converted to the original operating frequency and returned to the host radio for subsequent processing. When the applique is switched out, the VHF/UHF radio operates at its normal range [Ref. 25].

Since being developed in 1986, the EHF applique has been operated with both VHF radios (AN/VRC-46, AN/VRC-64, and AN/VRC-87 (SINCGARS)) and UHF radios (AN/URQ-33, and AN/WSC-3) [Ref. 25].

3. Air-to-Air Applications

In 1979, a U.S. Air Force, EHF Air-to-Air Communications Techniques Program was established to examine the utility of air-to air LPI communications (see Figure 14). The program was partitioned into areas of study which included:

- an analysis of EHF propagation effects,
- a review of EHF component technology,
- an investigation of EHF mission applications, and
- a performance analysis of a baseline design.

The strategic and tactical scenario analysis conducted during the program have produced several EHF applications for short range antijam (AJ) and LPI

communications. The most extensive research was performed on tactical fighter missions with approximately 90 formations analyzed with respect to maximum communication range and flight dynamics.

A baseline EHF tactical air-to-air communications system was defined as a result of the program and link power budget calculations were made to determine the maximum allowable attenuation. Two important conclusions of the Air Force program are:

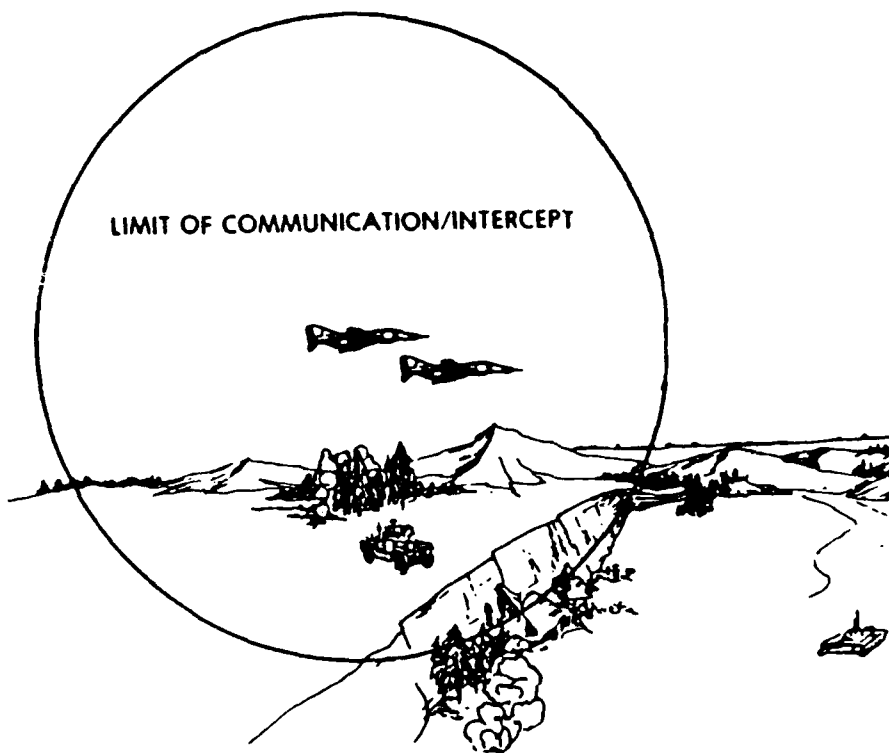


Figure 14. EHF Air-to-Air Communication Concept [Ref. 26]

- that EHF frequencies can be used to meet USAF mission requirements and provide AJ/LPI communications, and
- that millimeter wave component development has reached a level of maturity which allows such a system to be built. [Ref. 26]

Appendix B contains additional information on the U.S. Air Force's EHF air-to-air program.

B. SATELLITE COMMUNICATIONS

The EHF Military Satellite Communications (MILSTAR) program is the most ambitious application of mm-wave communications ever undertaken by the U.S. Government. As depicted in Figure 15, the satellite system will have uplinks at 44 GHz and downlinks at 20 GHz. The satellites will have switchable multibeam antennas with narrow beamwidths and low sidelobes [Ref. 27]. The use of these high frequencies, together with moderate sized antennas on the satellite, will enable small areas to be illuminated on the earth. This LPI capability will help reduce the possibility of signal intercept by an enemy. When it is fully deployed, there will be seven or eight satellites relaying AJ/LPI communications between thousands of user terminals on vehicles, aircraft, ships, and submarines. [Ref. 27]

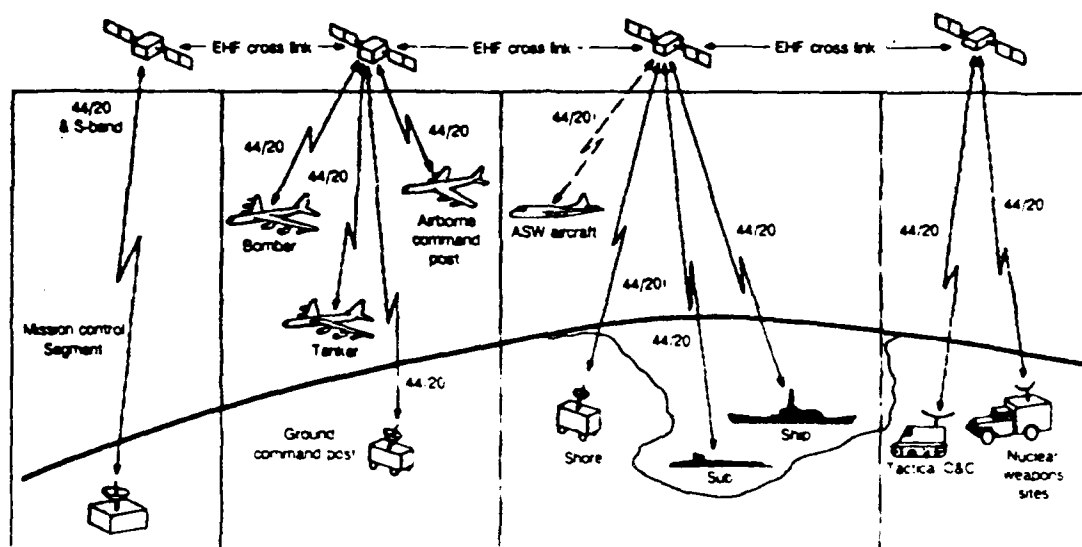


Figure 15. MILSTAR Communications [Ref. 27]

V. EHF LPI LINK ASSESSMENT

A. A STRUCTURED EHF LPI ASSESSMENT

Because reliable communications are essential to success on the battlefield, evaluating the effectiveness of a LPI communication system is an important tactical planning and employment consideration. The purpose of a LPI communications system is to degrade the effectiveness of enemy electronic counter measures (ECM) and electronic support measures (ESM) which are designed to locate, disrupt, and destroy the system.

In addition to short-range applications, tactical scenarios in which LPI communications can be effectively employed include:

- satellite or airborne relay links to high-value units such as a ballistic missile submarine or a tactical command post, and
- critical, command and control satellite links between tactical forces and the National Command Authority.

Preventing the exploitation of these critical communication links is an important LPI consideration because these assets are likely targets for ESM and ECM activity.

1. Three LPI Scenarios

The position of the enemy interceptor with respect to the targeted emitter is an important factor in a LPI system vulnerability assessment. In many cases, the most effective interceptor platform is an aircraft operating at an altitude which provides a wide coverage of the targeted area.

Figure 16 illustrates the relative positions of an LPI scenario which includes an airborne command post, a satellite, and an enemy interceptor. Figure 17 depicts a LPI scenario which includes a naval task force, an airborne radio relay, and attacking aircraft. Figure 18 shows a submarine, a satellite, and an enemy interceptor LPI scenario.

2. System Parameters and Performance

Using link analysis and the scenario shown in Figure 16, the LPI performance of EHF and SHF satellite up-link transmissions were compared [Ref. 28]. Table 9 lists several of the link parameters used in the analysis. Figure 19 shows the intercept range for the EHF and SHF transmissions plotted versus the ratio of the interceptor bandwidth (W_I) to the total available bandwidth for the respective emitters (W).

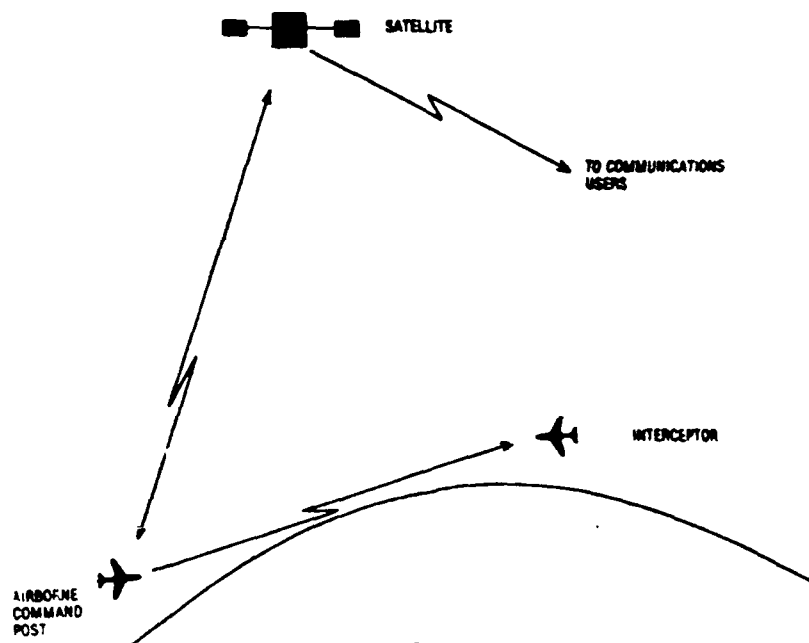


Figure 16: Airborne Command Post Scenario [Ref. 28]

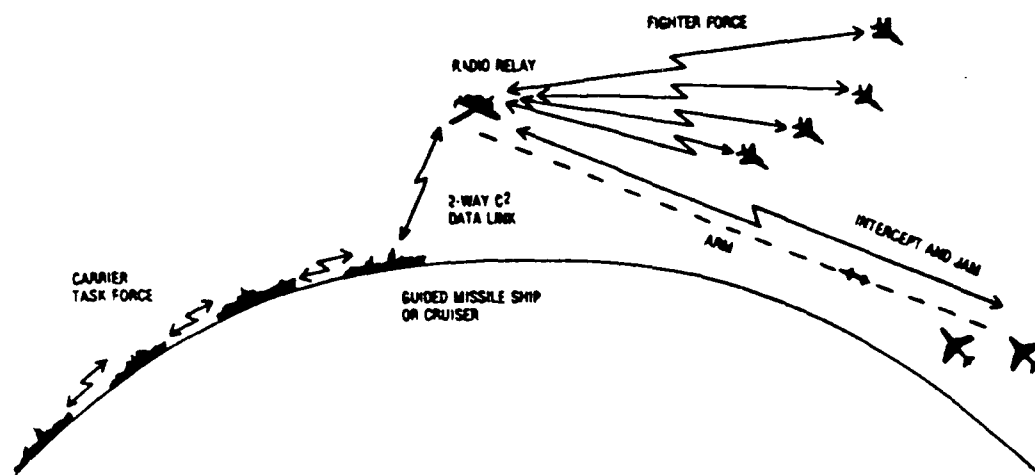


Figure 17. Task Force LPI Scenario [Ref. 28]

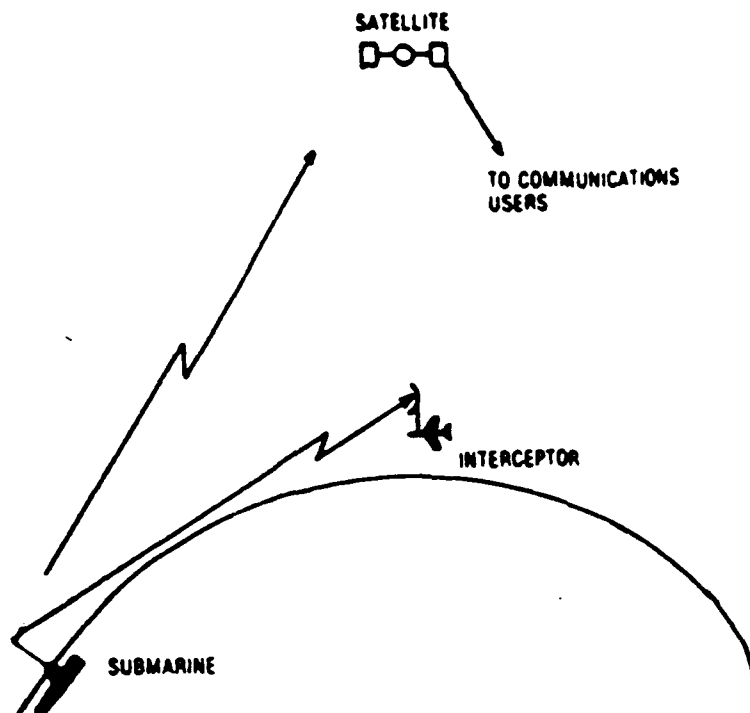


Figure 18. Submarine LPI Scenario [Ref. 28]

As shown in Figure 19, when the ratio of W_1/W is one, the intercept range for the scenario in Figure 16 is 37 nmi at 8 GHz (SHF) and 7 nmi at 44 GHz (EHF). Appendix C contains additional system performance specifications and information concerning the procedure used for the link analysis.

TABLE 9. LINK PARAMETERS [Ref. 28]

- Up-link Frequencies; EHF: 44 GHz, SHF: 8 GHz
- Transmission bandwidths; EHF 2 GHz, SHF: 500 MHz
- Interceptor range determined from a probability of detection of 90 % and a false alarm rate of 10^{-10}
- Transmission is from a airborne CP with a parabolic antenna with a diameter of 3 feet.
- The interceptor uses a chip radiometer system with multibeam antenna beamwidths which are equivalent to a parabolic dish antenna of 0.5 feet in diameter.
- The altitudes of the airborne interceptor and CP are 60,000 and 40,000 feet respectively.

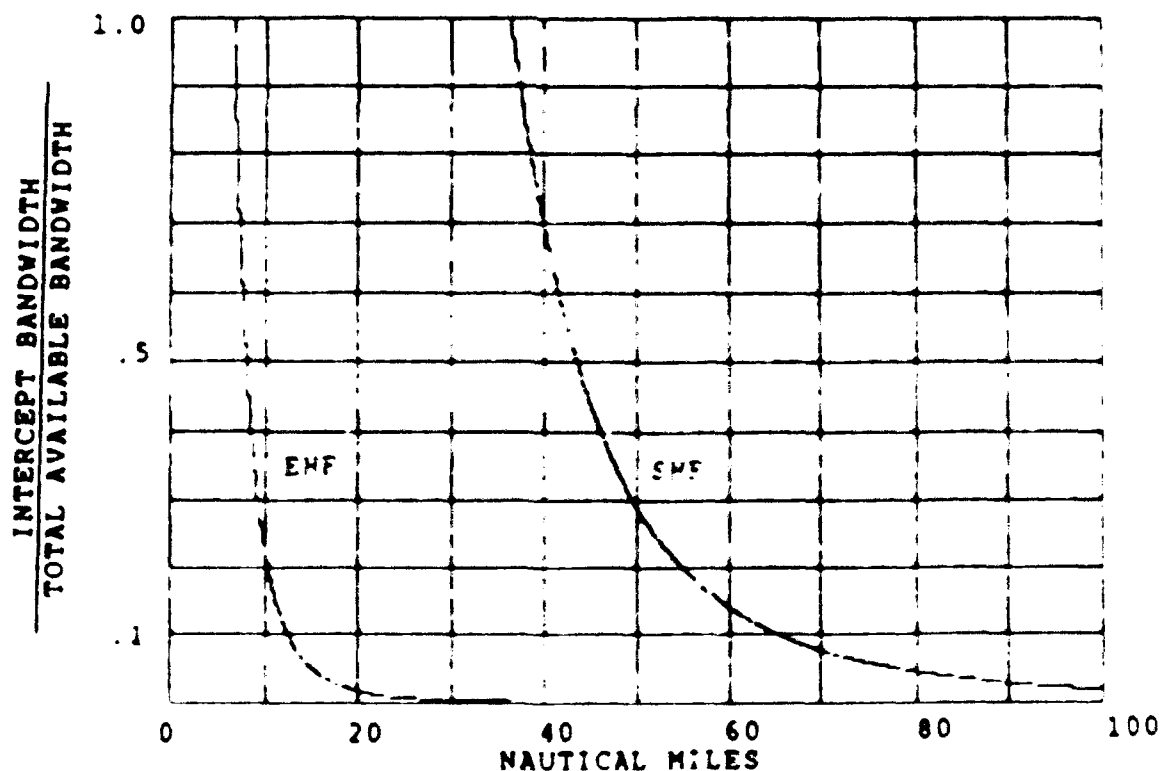


Figure 19. EHF and SHF Intercept Range

B. A PROPOSED EHF LPI ASSESSMENT SYSTEM: IREPS

1. Introduction

The Integrated Refractive Effects Prediction System (IREPS), developed by the Naval Ocean Systems Center (NOSC), provides shipboard environmental-data processing and display capability for electromagnetic wave propagation assessment. The application programs are designed for naval surveillance, communications, electronic warfare, and weapons guidance systems. These propagation assessment programs are of the same type and format that are needed to effectively plan and implement tactical, EHF LPI communication links. Currently however, because it does not have an algorithm which can model the effects of atmospheric absorption, IREPS programs are limited to frequencies below 20 GHz. [Ref. 29]

2. An EHF Propagation Model

In the NOSC Technical Report 1300 dated October 1989, Ken Anderson makes the following recommendation concerning a mm-wave numerical propagation model:

The accuracy of the propagation model provides a strong justification for using it to assess propagation characteristics of millimeter wave communication and radar systems operating in many, if not all, ocean regions [Ref. 12]

Based on a comparison with the results of 2000 hours of actual EHF radio frequency measurements, Anderson further states that

...the increase in received signal strength due to the presence of the evaporation duct has been realistically modeled and provides an accurate estimate of actual millimeter wave system performance. The significant system "gain" due to evaporation ducting is clearly an important consideration in the design stages of moderate range, over-water millimeter wave systems. [Ref. 12]

The integration of a mm-wave propagation algorithm into IREPS would make the LPI assessment programs described in the following section applicable to EHF as well as UHF and VHF systems.

3. IREPS LPI Assessment

IREPS contains a utility program which can calculate the maximum intercept range for UHF and VHF communication systems. The IREPS ESM intercept-range table can display the maximum intercept range of specified emitters by a specified ESM receiver. Figure 20 shows an example of an ESM intercept-range table. [Ref. 29]

For LPI planning purposes, if a commander wants to assess the ESM vulnerability of his entire platform or unit, the use of the IREPS's vulnerability assessment display allows a quick interpretation of the significance of the data contained in the ESM intercept-range table shown above.

EMITTER	FREQ (MHz)	MAXIMUM INTERCEPT RANGE (nm)	EMITTER	FREQ (MHz)	MAXIMUM INTERCEPT RANGE (nm)
ONE	125	31	NINETEEN	8000	3
TWO	125	55	TWENTY	8000	8
THREE	125	66	TWENTY-ONE	8000	69
FOUR	125	55	TWENTY-TWO	8000	2
FIVE	125	66	TWENTY-THREE	8000	13
SIX	125	78	TWENTY-FOUR	8000	18
SEVEN	125	66	TWENTY-FIVE	8000	18
EIGHT	125	79	TWENTY-SIX	8000	22
NINE	125	96	TWENTY-SEVEN	8000	97
TEN	200	5	TWENTY-EIGHT	15000	5
ELEVEN	200	32	TWENTY-NINE	15000	11
TWELVE	200	47	THIRTY	15000	42
THIRTEEN	200	7	THIRTY-ONE	15000	5
FOURTEEN	200	18	THIRTY-TWO	15000	15
FIFTEEN	200	58	THIRTY-THREE	15000	250+
SIXTEEN	200	11	THIRTY-FOUR	15000	17
SEVENTEEN	200	21	THIRTY-FIVE	15000	23
EIGHTEEN	200	58	THIRTY-SIX	15000	25

Figure 20. IREPS Intercept Range Table [Ref. 29]

From this display, it is immediately obvious which emitter is most vulnerable to intercept. By selectively switching emitters to the EHF spectrum (EHF applique option), the commander would be able to design : LPI communication plan to fit the needs of a particular mission. Figure 21 shows an example of an IREPS platform vulnerability display.

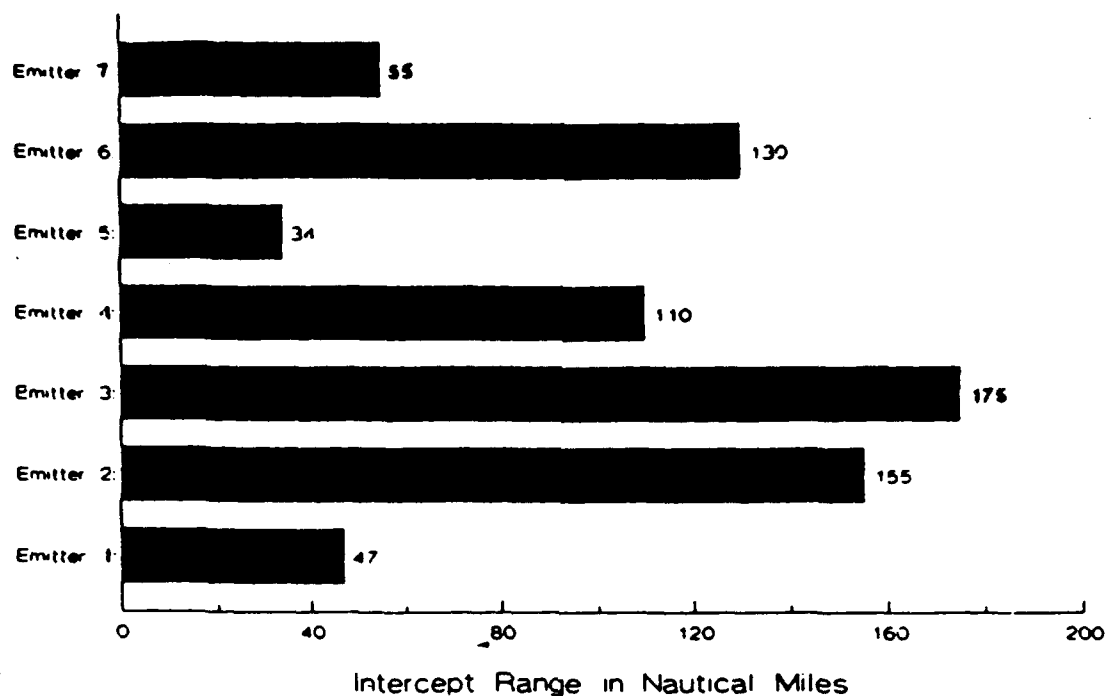


Figure 21. Platform Vulnerability Display [Ref. 29]

In addition to the displays shown above, an EHF enhanced version of IREPS would also provide the following assessment programs which are pertinent to EHF LPI communication planning:

- Propagation Conditions Summary,
- Radio Coverage,
- Radio Path Loss,
- ECM Effectiveness, and
- Battlegroup Vulnerability Assessment.

VI. SUMMARY AND CONCLUSIONS

A. EHF LPI ADVANTAGES AND DISADVANTAGES

In general, both EHF terrestrial and satellite communication systems provide capabilities and limitations which are based on the three fundamental characteristics of millimeter waves:

- short wavelengths,
- large bandwidths, and
- atmospheric propagation effects,

These three characteristics may provide advantages and/or disadvantages, depending upon the specific requirements of the application.

1. Advantages

The advantages of the EHF spectrum for LPI communications are:

- Smaller wavelengths, which allow a reduction in component size resulting in compact systems, and narrow beamwidths which provide the receiver with high immunity from jamming.
- Wide bandwidths which allow high information rate capability, wide-band spread-spectrum capability, and high immunity to jamming due to the large number of frequencies that can be used.

- Propagation characteristics which allow:

- (1) low attenuation losses in transmission windows compared to IR and optical frequencies,
- (2) high absorption around transmission windows which provides LPI protection and difficulty in long-range jamming,
- (3) low terrain scatter which results in lower multipath interference, and
- (4) negligible attenuation in dust, smoke and the atmospheric debris commonly associated with battlefield conditions.

2. Disadvantages

The limitations of the EHF spectrum for LPI communications are:

- Smaller wavelengths resulting in increased cost due to the need for greater precision with small components.
- Propagation characteristics which cause reduced capability in adverse weather.

B. EHF LPI SYSTEMS AND TECHNOLOGY TRENDS

1. Systems

On the modern battlefield, there is a need for reliable, covert, tactical communications [Ref. 30]. Figure 22 depicts the basic EHF LPI concept. There are many short-range tactical applications that could benefit from EHF LPI communication systems; however, the state of technological

development for EHF systems is less mature than that of other communication systems. Although numerous EHF LPI communication systems have been shown to fill a need, and several systems have been developed, production of EHF LPI systems for the widespread tactical applications shown in Figure 21 has not yet proven to be economically feasible. This problem is being addressed by current EHF research and development programs.

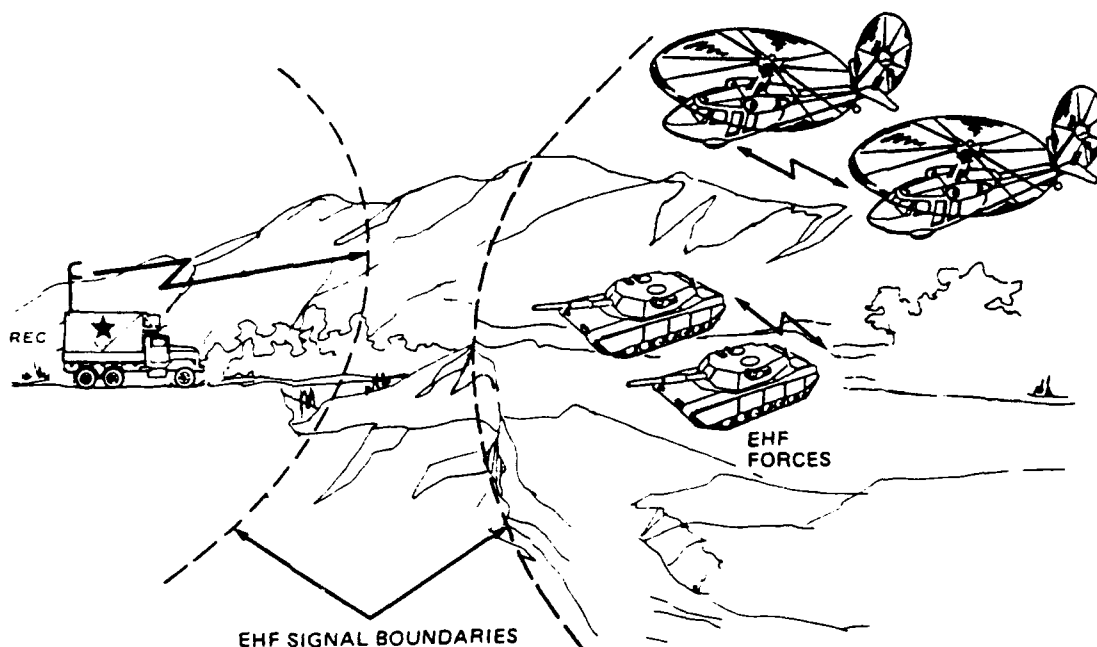


Figure 22. Radio Electronic Combat (REC) [Ref. 22]

2. Technology Trends

Recent technological advances in millimeter wave system and component design have been significant. One of

the most promising areas of technological development has been made as a result of the Department of Defense sponsored MMIC program. As shown in Chapter 3, MMIC device technology is providing the capability for complex signal processing in millimeter wave system applications. System impact studies and long range trend analyses predict that an order of magnitude improvement in signal processing throughput will occur in the next five years [Ref. 21]. MMIC solid-state technology is not only the most dynamic area of improved EHF system performance, it is also the most crucial for making EHF LPI communication systems economically feasible.

C. EHF LPI LINK ASSESSMENT

In order to provide reliable and effective LPI communications, EHF LPI system performance must be predictable. For naval LPI applications, the possible effects of evaporation ducts on the range of EHF transmissions must be considered. The integration of an mm-wave propagation algorithm into IREPS is one way of providing the tactical commander with a rapid-response, on-scene, EHF LPI link assessment capability.

APPENDIX A: EHF LPI PROGRAM

This appendix contains additional information on the U.S. Army Communications-Electronics Command's research and development effort for EHF communications. The information was extracted from "U.S. Army's Tactical EHF Thrusts," Proceedings of IEEE Southcon/83, January 1983, by J.R. Christian, J.W. Strozyk, and M. Schwartz [Ref. 31]

Table 10 shows a list of U.S. Army proposed tactical applications for EHF communication systems.

TABLE 10. POTENTIAL EHF APPLICATIONS

- Short Range Multichannel Transmission Systems
- Antenna/Command Post Remoting
- Remote Surveillance Information Transfer
- Artillery Communications/Data
- Special Forces Operations
- Covert Armor Platoon/Task Force C³
- Aircraft-Aircraft/Ground Links
- IFF/Communications Systems
- Dispersed Command Post

Figure 23 shows the various climate zones. Table 11 shows the worldwide transmission ranges predicted for an EHF radio having 20 and 32 dB gain margins for given link availabilities.

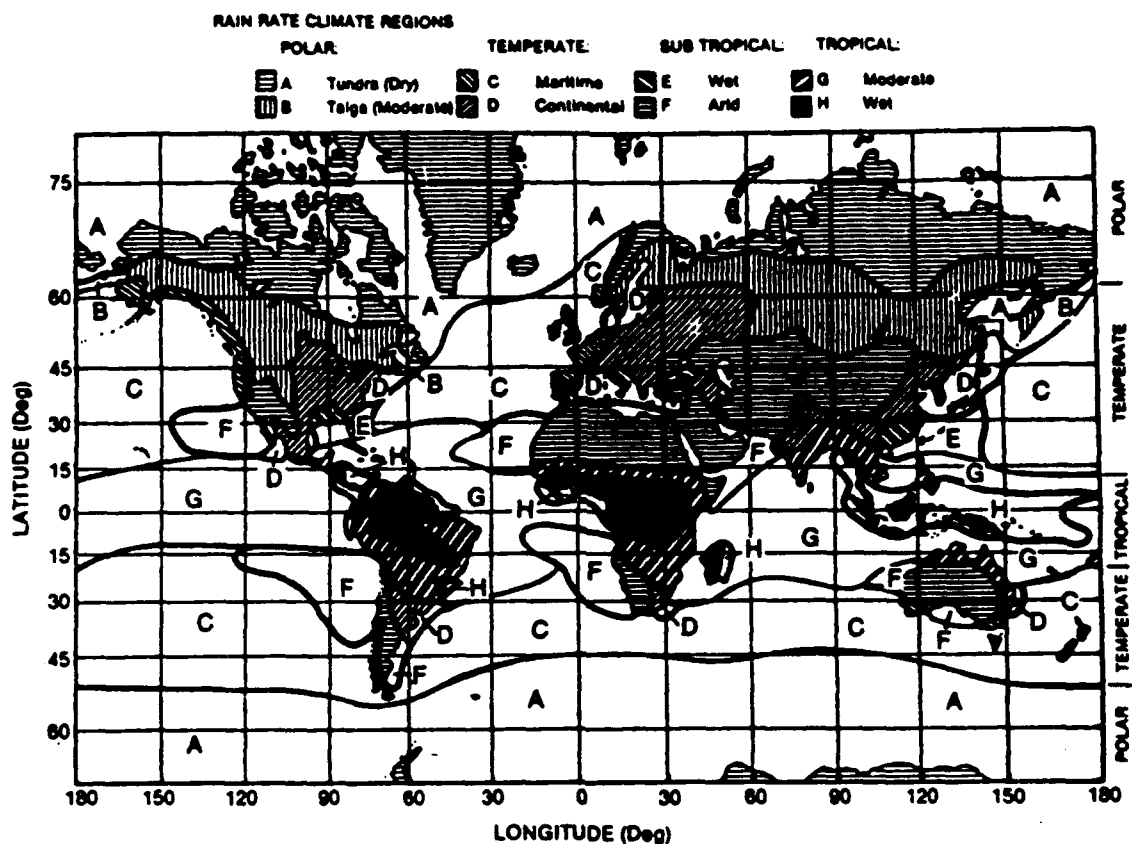


Figure 23. Global Rain Rate [Ref. 31]

TABLE 11. ESTIMATED RANGE FOR CLIMATE ZONES [Ref. 31]

Climate Zone	Availability			
	20 dB Margin @ 8 km		32 dB Margin @ 8 km	
	99.90%	99.95%	99.90%	99.95%
A Tundra	10.7 km	8.5 km	16.0 km	12.3 km
F Dry	10.7	8.5	16.0	12.3
B Moderate	9.2	7.5	14.0	10.7
D ₁ Continental	6.7	5.3	9.8	7.3
D ₂ Continental	5.5	4.3	7.8	5.8
D ₃ Continental	4.3	3.4	5.8	4.5
G Moderate	4.3	3.4	5.8	4.5
E Wet	3.1	2.2	4.2	2.8
H Wet	2.5	1.8	3.2	2.3

Table 12 shows a list of the EHF radios that CECOM has developed, purchased and evaluated since 1976.

TABLE 12. CECOM EHF RADIO SYSTEMS (DEVELOPMENTAL) [Ref. 31]

<u>MMW Radio Systems (Developmental)</u>					
<u>Frequency</u>	<u>Bandwidth</u>	<u>Format</u>	<u>Configuration</u>	<u>Contractor</u>	<u>Year</u>
60 GHz	20 MB/s	Simplex	Tripod-Mount	Lab Built	76
36 GHz	50 MB/s	Duplex	Rack-Mount	HAC	77
37 GHz	5 MHz	Simplex	Hand-Held	Norden	78
	1.5 MB/s	Duplex	Tripod	Norden	78
60/62 GHz	20 MB/s	Simplex	Rack-Mount	AIL	78
38 GHz	20 MB/s (TV)	Duplex	Mast-Mount	Norden	78
37 GHz	1.15 MB/s	Duplex	Tripod	Norden	78-79
54 GHz	Voice, IFF	Net	Omni	Norden	80
54 GHz	Voice, IFF	Simplex	Hand-Held	Norden	80
38 GHz	20 MB/s	Duplex	Mast-Tripod	Norden	80
36-38.6 GHz	20 MB/s	Tri-Tac	Militarized	Norden	80-82
		Compatible	6.3A		
54-58 GHz	5 MB/s	Duplex	Electronic	ITT	80-82
			Tunable	HAC	
				Norden	
55-57 GHz	576 KB/s	TDMA	Distribution System	Motorola	82-84

APPENDIX B: AIR-TO-AIR COMMUNICATION

This Appendix contains additional information on the U.S. Air Force's EHF Air-to-Air Communications Techniques Program. The information was extracted from "EHF Air-to-Air Communications Techniques," Rome Air Development Center TR 82-314, Air Force Systems Command, Vols. I and II, and "EHF Air-to-Air Communications," AGARD Conference Proc. No. 363, June 1984 by P.N. Edraos [Ref. 26]. As a result of the Air Force Program, the parameters in Table 13 were selected for the baseline air-to-air EHF radio.

TABLE 13. BASELINE PARAMETERS [Ref. 26]

<u>PARAMETER</u>	<u>SYMBOL</u>	<u>16 KBPS</u>	<u>2.4 KBPS</u>
Receiver Noise Temperature	T_e	1500 deg K	1500 deg K
Receiver Noise Figure	F	8 dB	8 dB
Data Rate	D	16 Kbps	2.4 Kbps
Detection Bandwidth	B	32 KHz	4.8 KHz
Thermal Noise Power	N_{th}	-122 dBm	-130 dBm
Transmitter Power Amplifier	P _{PA}	40 dBm	40 dBm
Transmitter Antenna Gain	G _{TX}	0 dB	0 dB
Receiver Antenna Gain	G _{RX}	0 dB	0 dB
Signal-to-Noise Requirement	S/N	9 dB	9 dB
Link Margin Allowance	LINKMARGIN	9 dB	9 dB
<hr/>			
Maximum Allowable Attenuation	ATTN _{max}	144 dB	152 dB

Once a baseline EHF tactical air-to-air communication system had been defined, the system was assessed in a number of different mission situations. The following portions of an air-to-air mission were evaluated:

- approach phase,
- entry into engagement area,
- mutual aircraft support during engagement, and
- withdrawal phase.

Figure 24 is the superposition of the maximum allowable attenuation for the 2.4 Kbps system on the attenuation curves for horizontal communications at an altitude of 2 km.

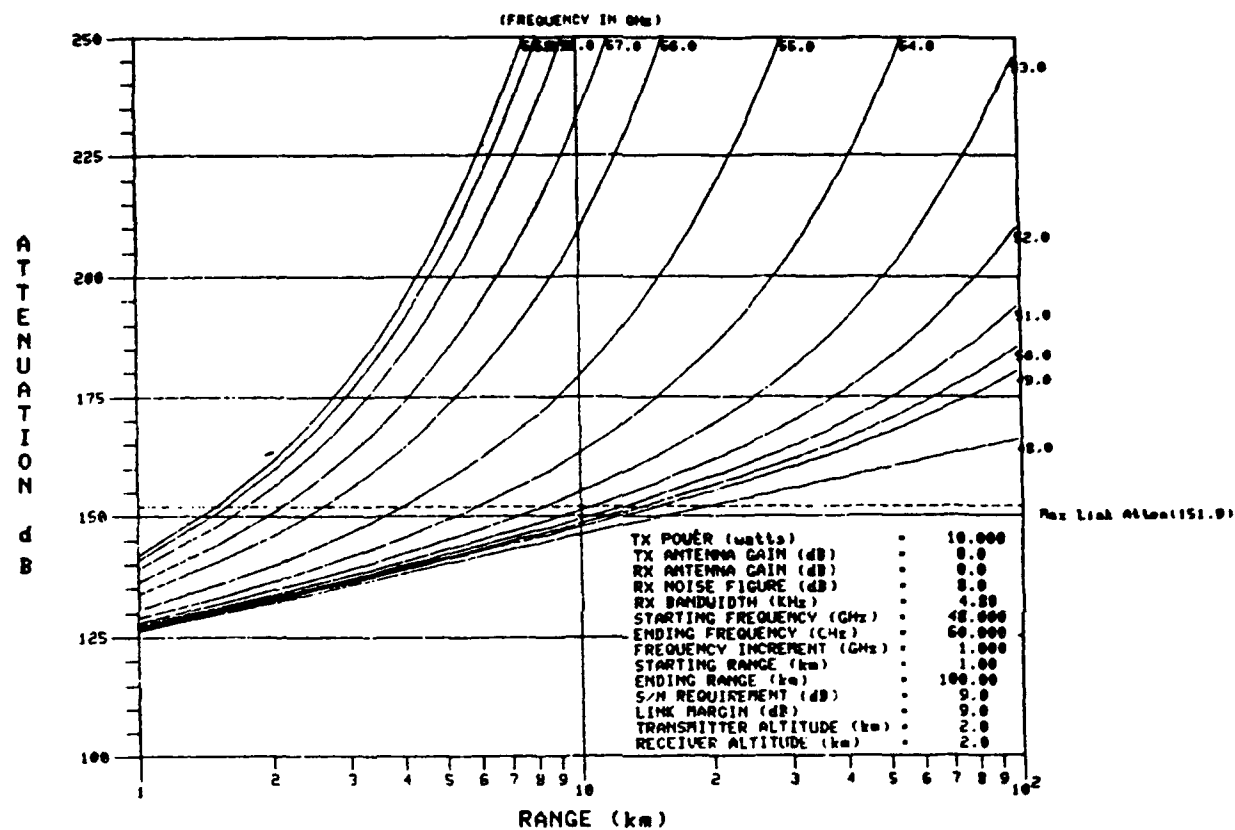


Figure 24. Approach Phase Horizontal Communications [Ref. 26]

Figures 25, 26 and 27 show the superposition of the maximum allowable attenuation for the 2.4 Kbps baseline system on the total attenuation curves for the entry, engagement, and withdrawal phases respectively.

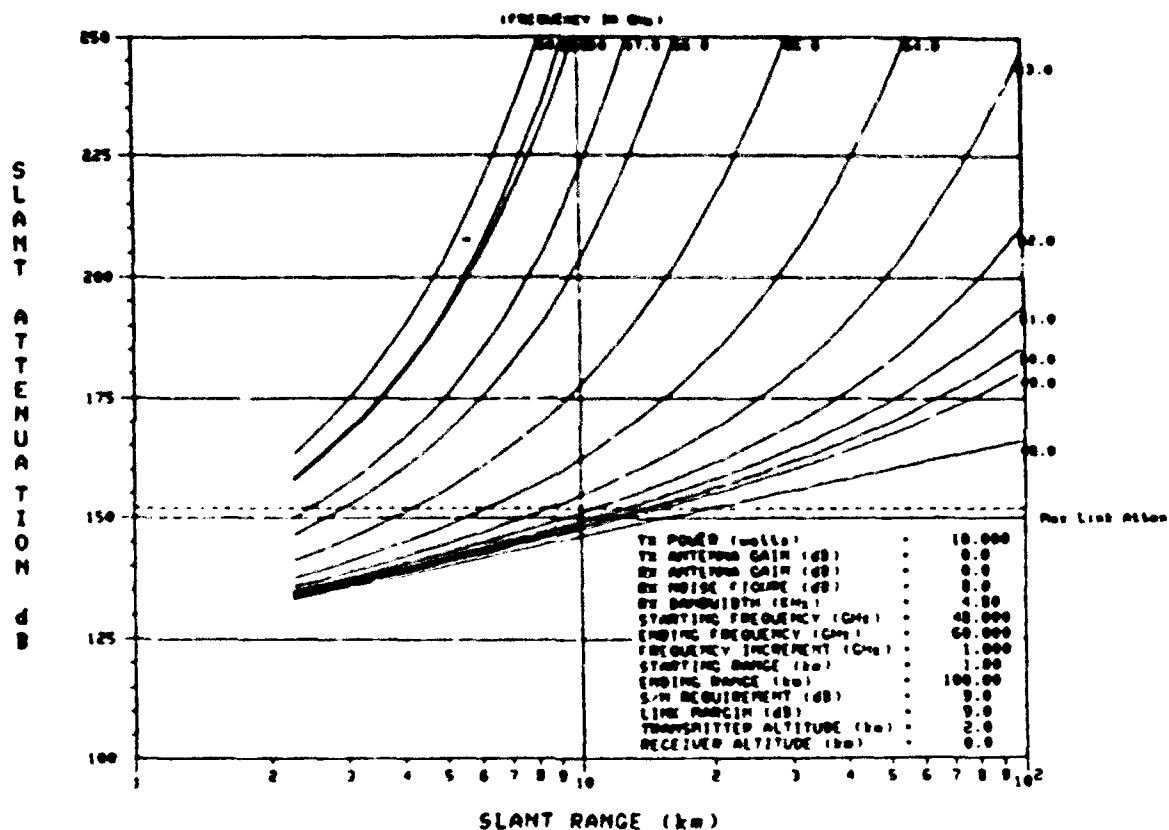


Figure 25. Entry Slant-Range Communications [Ref. 26]

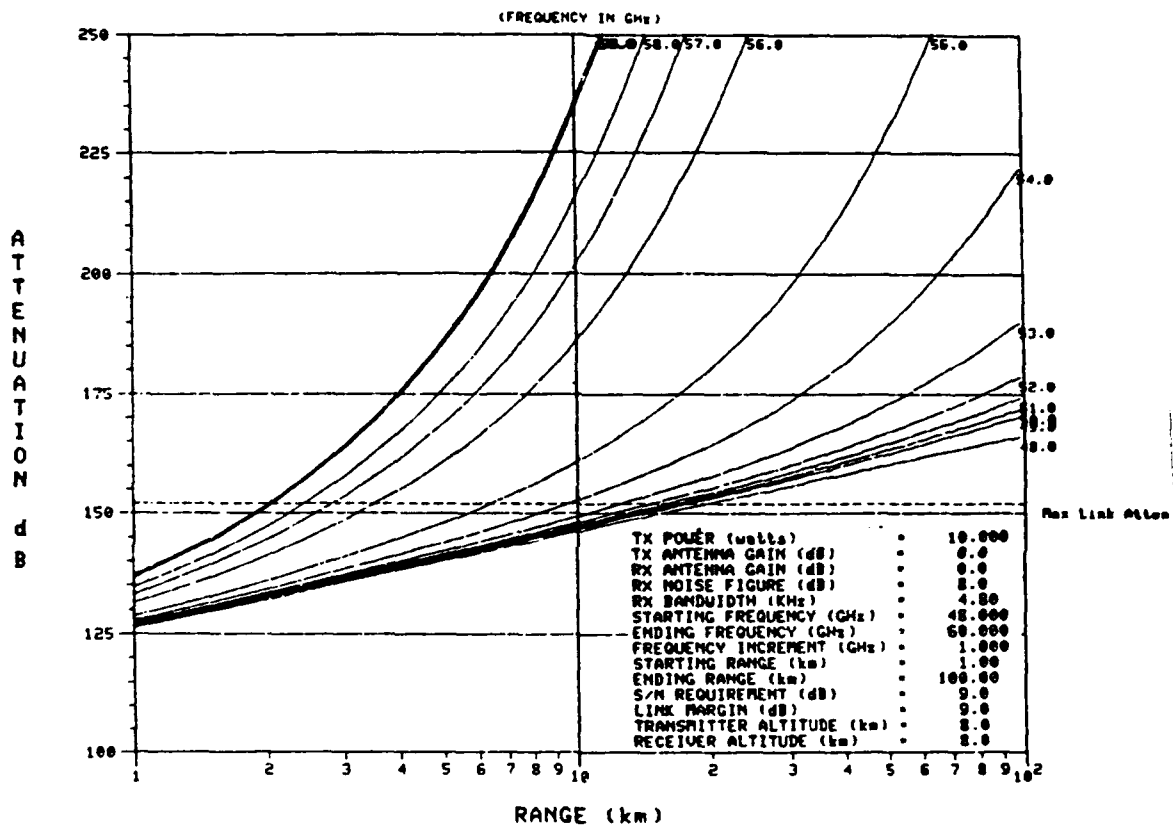


Figure 26. Engagement Horizontal Communications [Ref. 26]

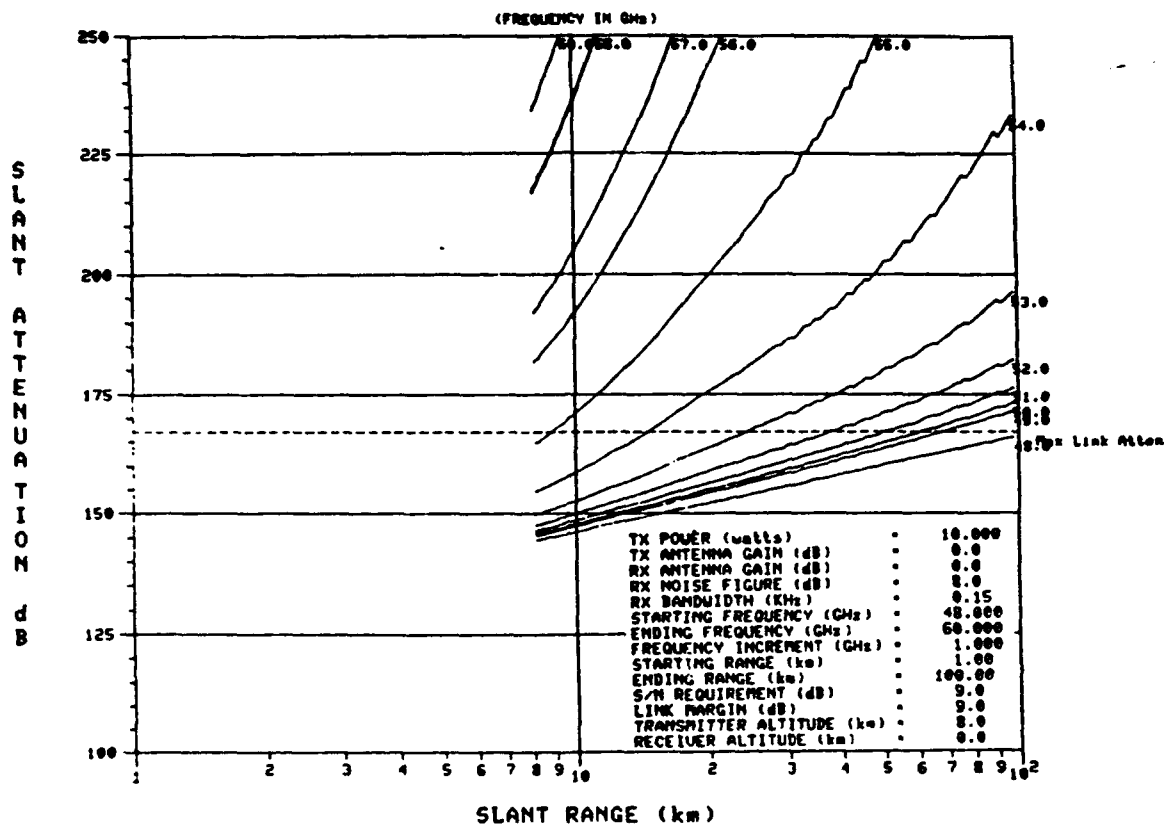


Figure 27. Withdrawal Slant-Range Communications [Ref. 26]

APPENDIX C: LINK ANALYSIS

The link analysis shown in Figure 18 is based on the method described in "Low Probability of Intercept," by A.B. Glenn [Ref. 26]. The information contained in this appendix is extracted from Appendix A of the reference.

The interceptor range (R1) between the airborne command post and the interceptor is given by:

$$R1 := R_s \left[\begin{array}{c} G_{it} \frac{L_s T_{sr} M}{L_l T_{ir} LL} \frac{E_{bs}}{No} (R_d N_d) \end{array} \right]^{.5} \frac{\left[\frac{G_{ir}}{G_{sr}} \right]^{.5}}{\left[\begin{array}{ccc} .5 & .5 & .25 \\ G_{st} & dt & W_l \end{array} \right]}$$

where,

R_s = Airborne command post to satellite range = 21,500 nmi

G_{it} = Gain of airborne CP's antenna in the direction of the interceptor
 = 5 dB at 8 GHz
 = 10 dB at 44 GHz

G_{ir} = Gain of the interceptor's receive antenna in the direction of the CP
 = 20 dB at 8 GHz
 = 33 dB at 44 GHz

Gst = gain of airborne CP's antenna in the direction of the satellite	= 35 dB at 8 GHz = 50 dB at 44 GHz
Gsr = gain of the satellite's receive antenna to the desired signal	= 46 dB at 44 GHz = 32 dB at 8 GHz
LL = correction factor in using Gaussian statistics in the output of the energy detector.	= 1
Ls = additional (above free space loss) on the up-link from the airborne CP to the satellite (such as rain, atmospheric loss).	= Ll
Ll = additional channel loss between the airborne CP and the interceptor.	= Ls
Tsr = system noise temperature of the satellite	= 1800 deg K
Tir = system noise temperature of the interceptor	= 435 deg K
M = airborne CP to satellite link margin	= 6 dB
Ebs/No = bit energy to noise-power spectral density at the satellite receiver	= 10 dB
Rd = message data rate	= 75 bps
Nd = number of message bits	= 40
f = frequency of transmitted signal (EHF)	= 44 GHz
(SHF)	= 8 GHz
dt = effective post-detection SNR in the interceptor receiver	= 8 dB
Wl = bandwidth of interceptor receiver	= < W

W = total transmission bandwidth = 2 GHz
(EHF)
(SHF) = 500 MHz
Dst = diameter of the airborne CP antenna = 3 feet

Since Gst is a parabolic antenna, its gain may be expressed as:

$$Gst = 5.9 Dst^2 * f^2$$

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